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Turning Points in Containment of Lawrence Livermore National Laboratory Underground Nuclear Tests

B.C. Hudson, J.T. Rambo, G.A. Pawloski, and N.R. Burkhard

November 2006

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Turning Points in Containment of Lawrence Livermore National Laboratory Underground Nuclear Tests

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November 20, 2006

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Sometime in 1987 Billy Hudson, a long-time LLNL Containment Scientist and the Task Leader for Containment Diagnostics, put together a presentation entitled "Turning Points in Containment". This presentation identifies challenges, lessons learned, and changes made in containment practice over a 20-year period, from 1967-1987. Besides providing a significant historical summary, the presentation is valuable as we maintain a position of readiness 14 years after the last underground nuclear detonation. It is particularly valuable to personnel who are new to the program and have no first-hand experience in implementing underground nuclear test containment for actual tests. We now view this material as a unique containment summary with timeless importance. We envision this report to be particularly useful to new Containment Program members and anyone interested in the history of underground nuclear test containment practices.

We believe that the Barnwell test, detonated in 1989, would have been added to this summary if Billy Hudson had the opportunity to update the presentation. We have chosen to add a few slides to the end of the original presentation to describe the issues and lessons learned from Barnwell.

John Rambo, Containment Program Archivist
Gayle Pawloski, Deputy Containment Program Leader
Norman Burkhard, Containment Program Leader
20-November-2006

Turning Points In Containment (20 Years in Perspective)

B. Hudson

Successful containment is defined as:

"Containment such that a test results in no radioactivity detectable off site as measured by normal monitoring equipment and no unanticipated release of radioactivity on site."

LTBT: Limited Test Ban Treaty

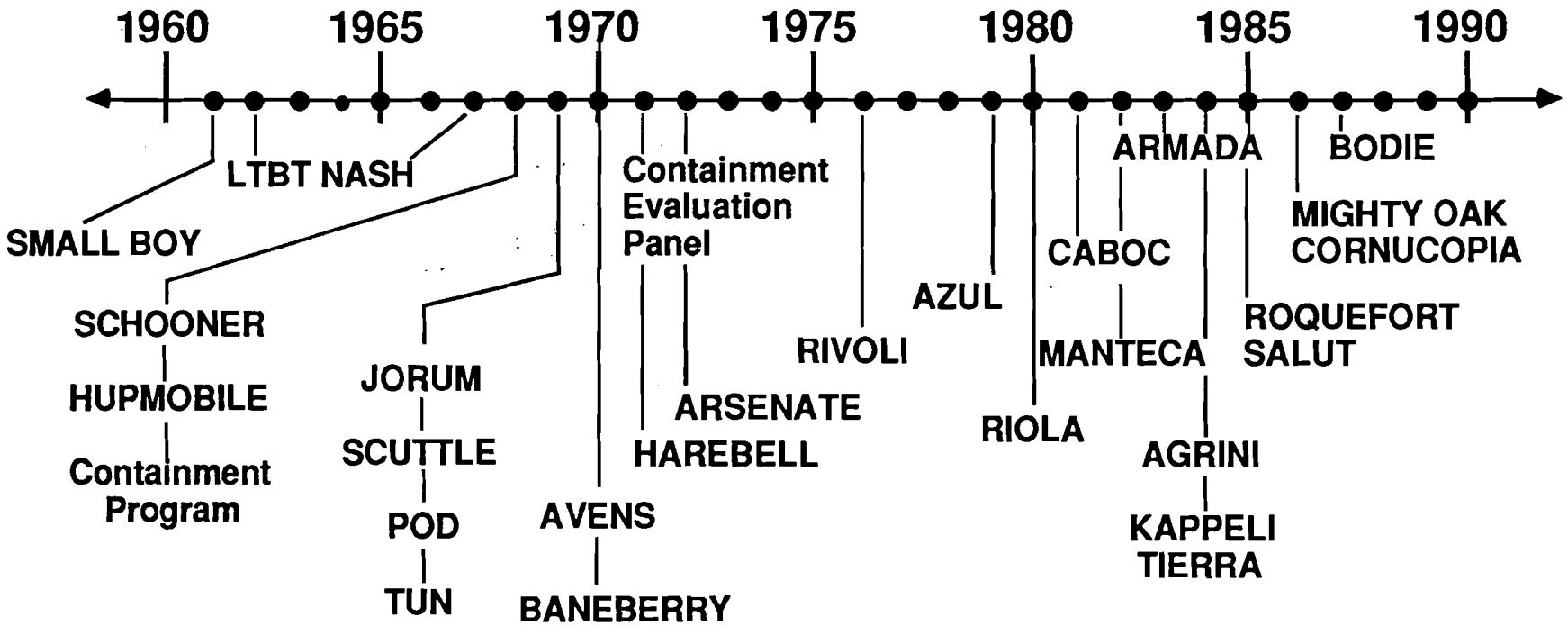
This treaty was signed by the U.S., the U.K., and the U.S.S.R. on August 5, 1963, and took effect on October 10, 1963, by which time 102 other nations had signed it.

This treaty prohibits any test"...if such explosion causes radioactive debris to be present outside the territorial limits of the state under whose jurisdiction or control such explosion is conducted."

This treaty bans:

- Tests in the atmosphere
- Tests in outer space
- Tests under water

Turning Points in Containment

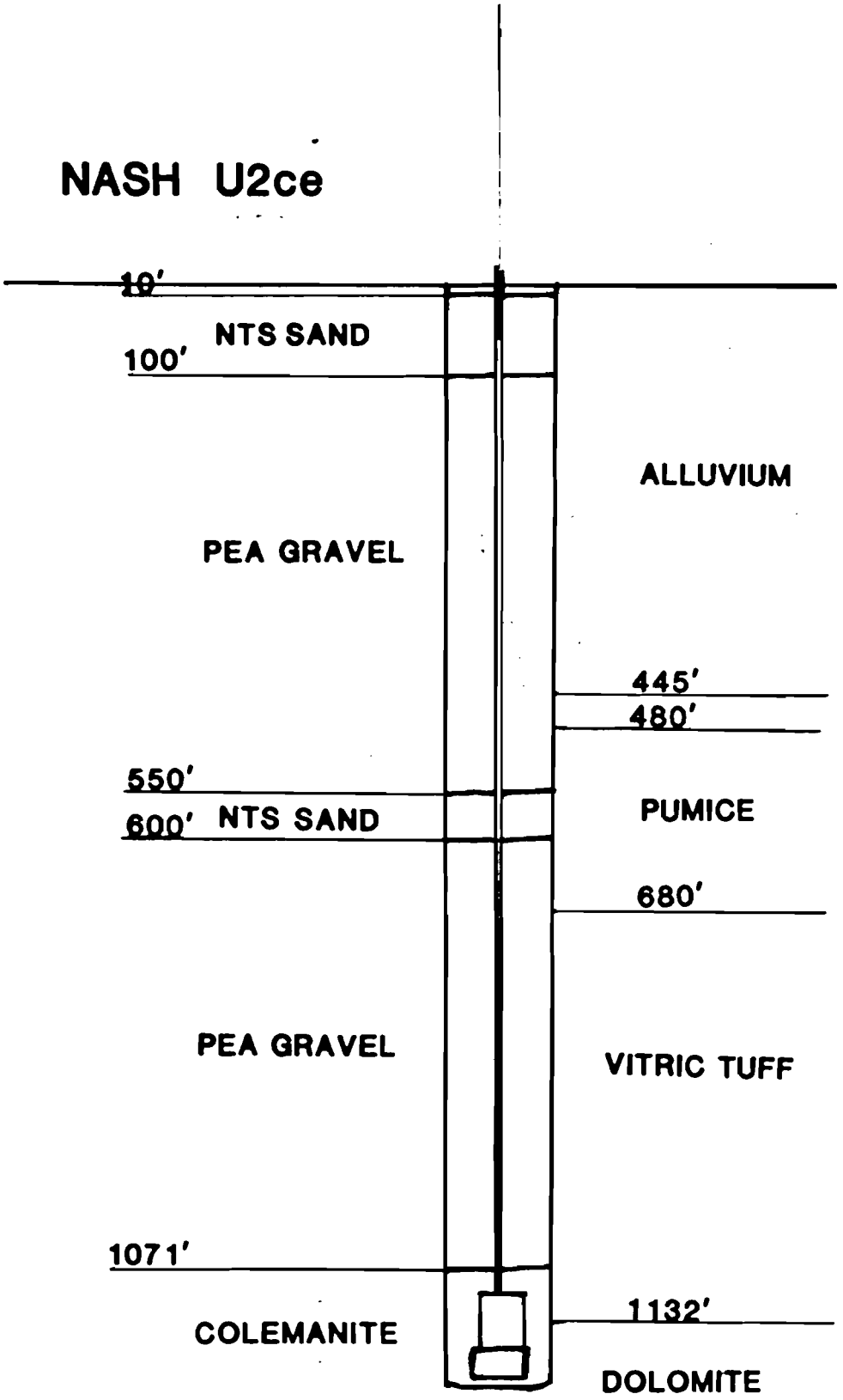


The time between leaks is 4 years

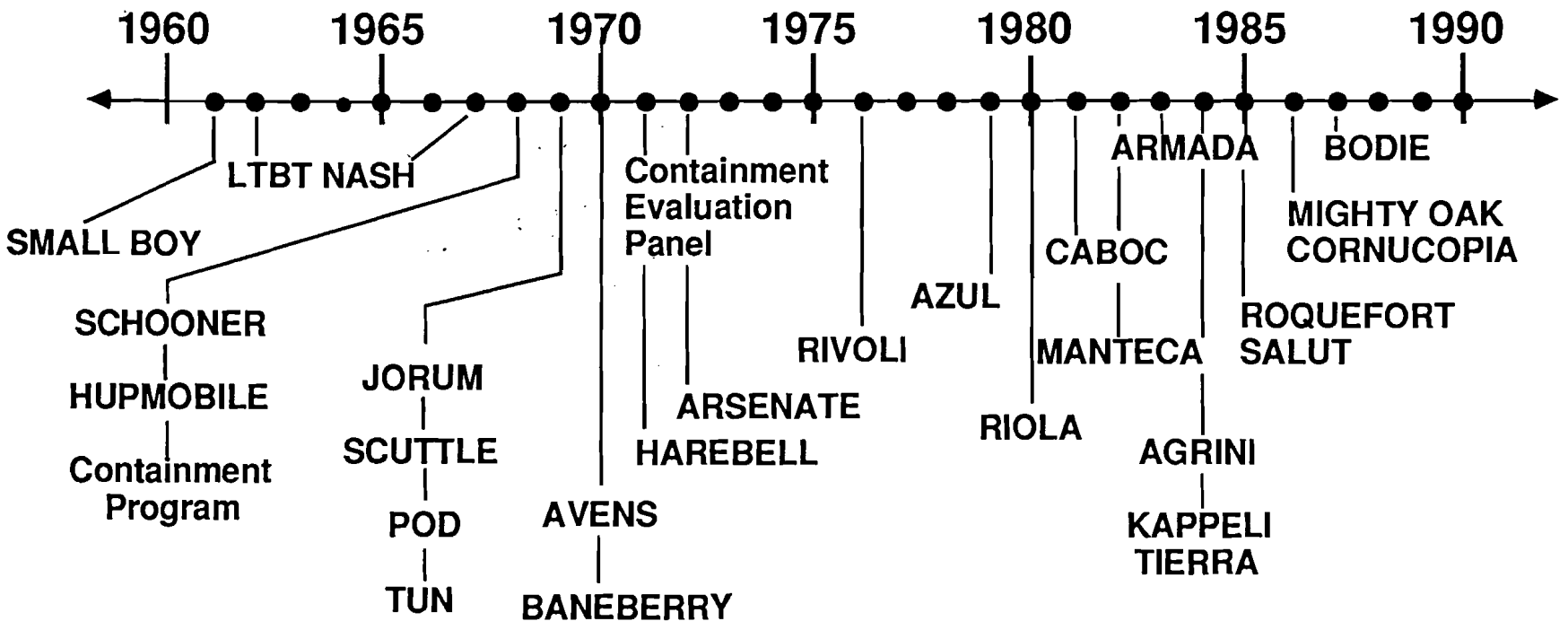
The NASH event involved a release due to non-condensible gas

- NASH was the highest yield event with a release detected off-site
- Surface subsidence occurred at 23 min., 57 sec.
- The release began at +9.2 hrs., lasted 41 hrs., and was detected off-site
- Nash was detonated in Dolomite, a mineral containing 45.8% CO_2 by weight

NASH U2ce


10'
NTS SAND
100'
ALLUVIUM
PEA GRAVEL
445'
480'
550'
PUMICE
600'
NTS SAND
680'
PEA GRAVEL
VITRIC TUFF
1071'
1132'
COLEMANITE
DOLOMITE

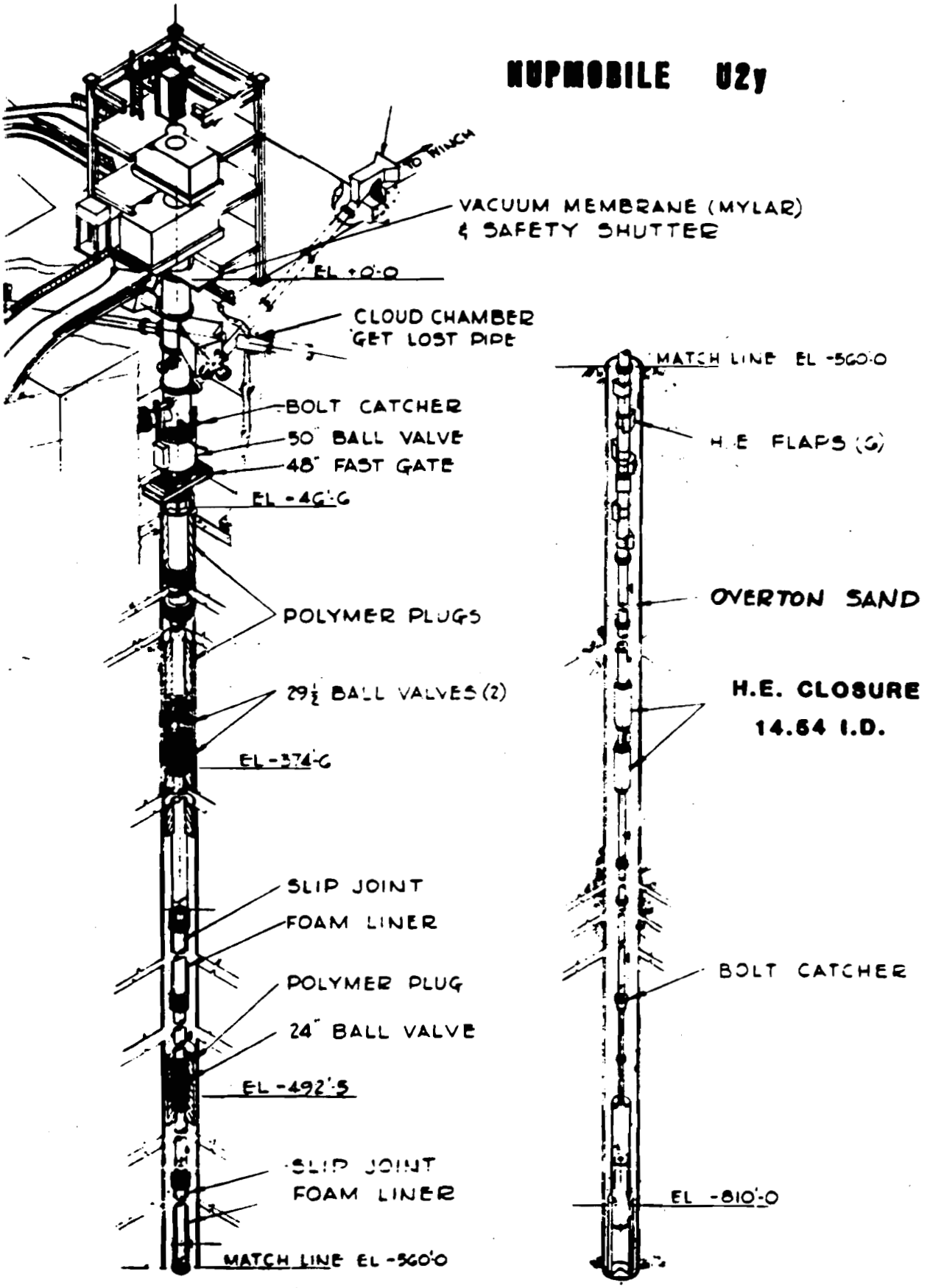
Turning Points in Containment



HUPMOBILE involved a release resulting in significant operational problems

- The "sled" that housed exposure experiments at the surface burned, essentially destroying the contents
- The released radioactivity (1.2×10^5 Ci) fogged film in the diagnostic trailers
- Harry Reynolds and Jim Carothers decided to form a Containment Program

HUPMOBILE U2y

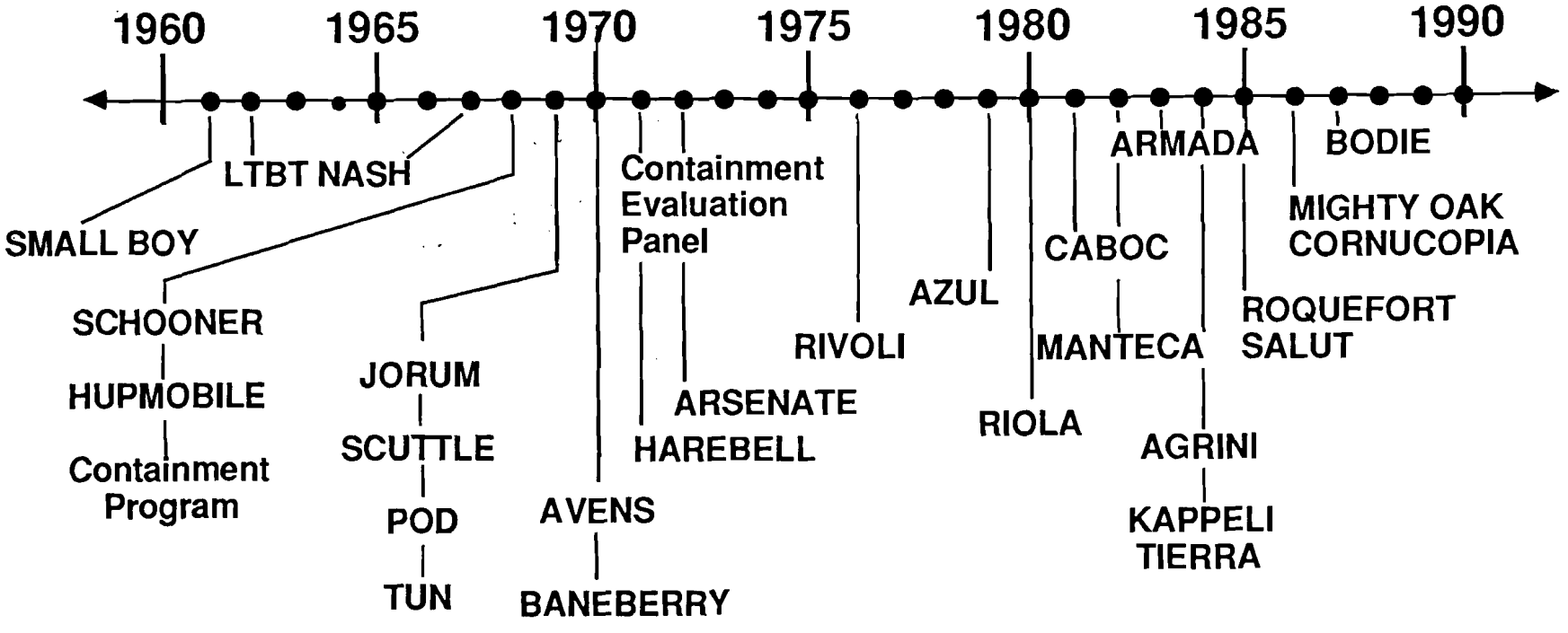


The newly formed Containment Program comprised:

- A group in L-Division under Bill McMaster.
- A group in NTED under Palmer House.
- A group in K-Division under Larry Ramspott.
- The Program Leader was Larry Germain.

The primary goals were to prevent such data losses as occurred on HUPMOBILE and satisfy the LTBT.

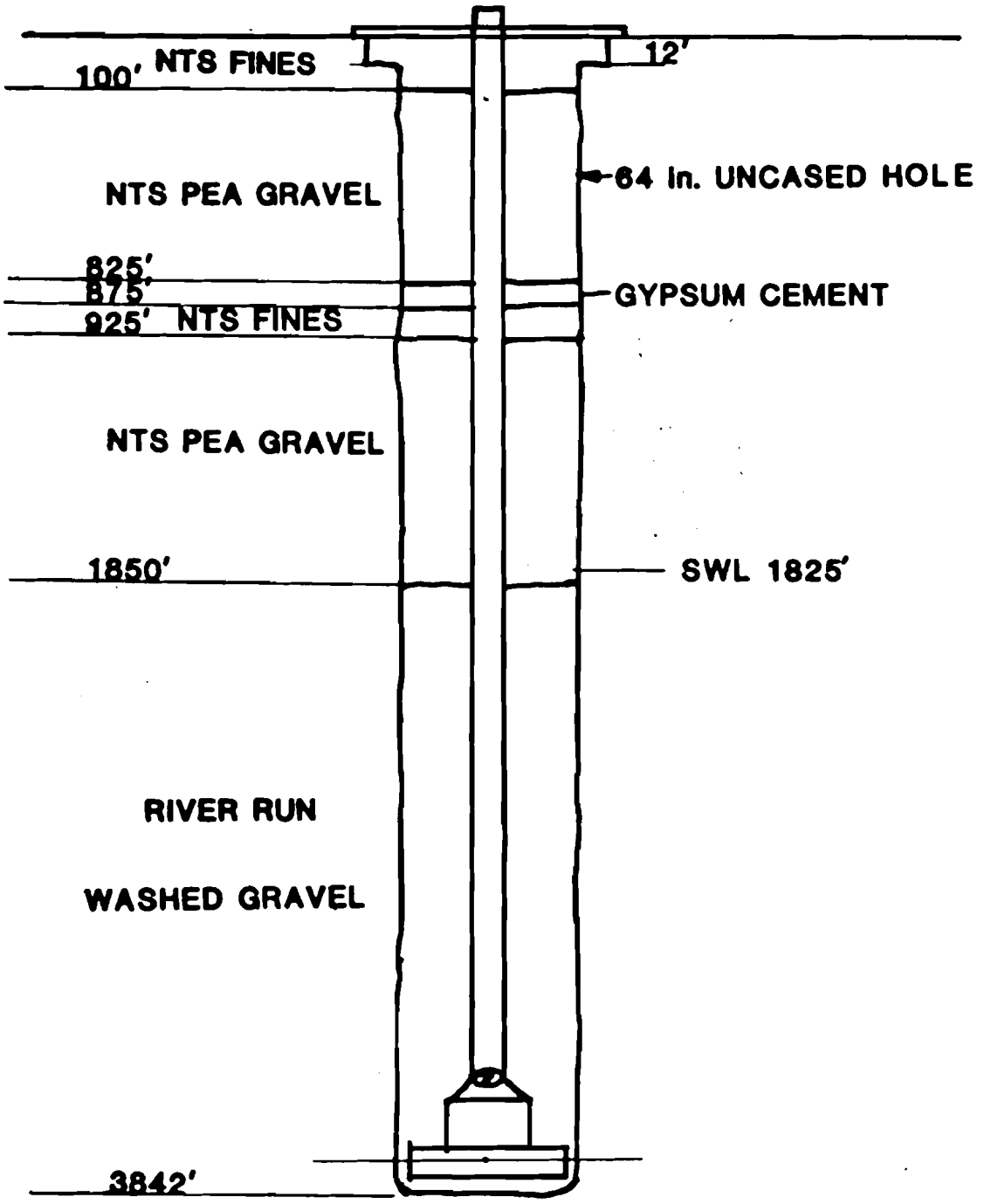
Turning Points in Containment



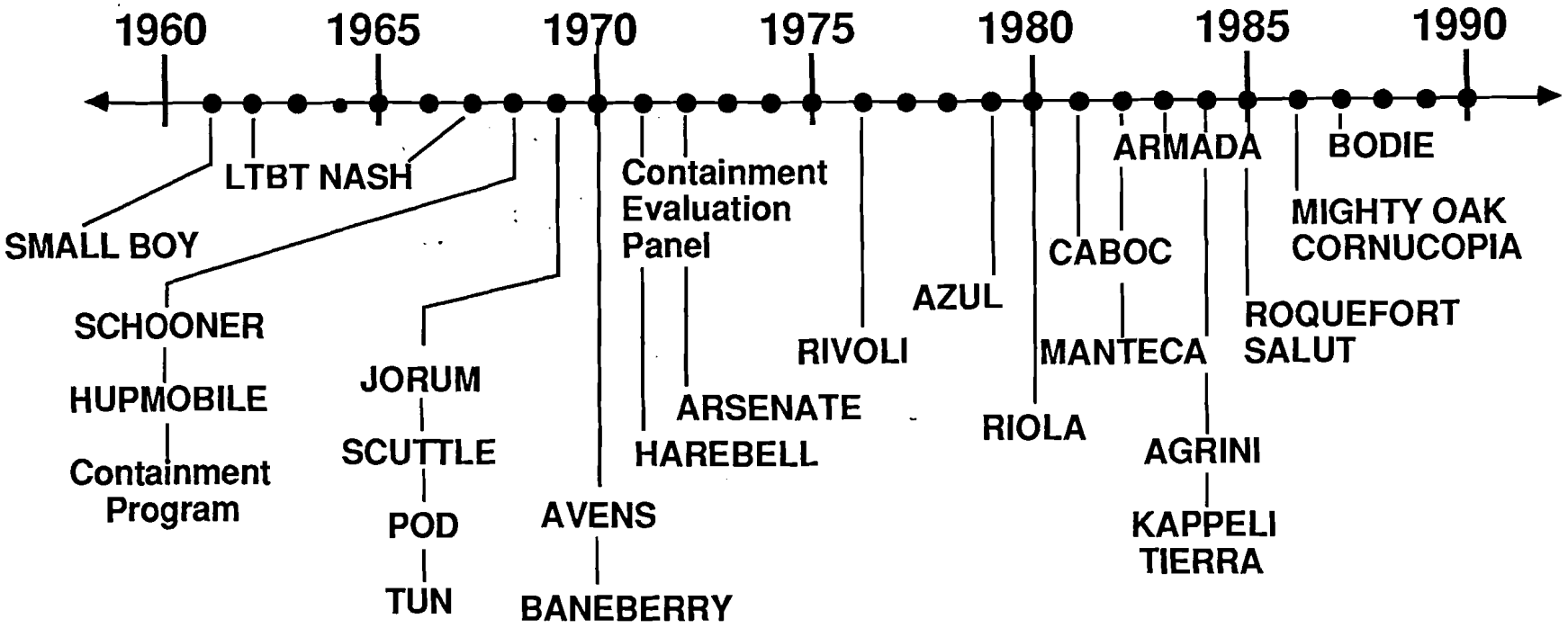
JORUM and similar high yield events posed what has become a typical containment problem

- Too much money was being spent on containment; in this case, depth of burial (DOB)
- A scaled depth of burial (SDOB) of 350 ft/kt$^{1/3}$ (107 m/kt$^{1/3}$) was believed to be overly conservative
- Jack Kahn attempted to persuade the Test Evaluation Panel (TEP) that a much lower SDOB would be adequate based on the "gas acceleration model"
- He was unsuccessful

JORUM U20e


100' NTS FINES
12'
64 In. UNCASED HOLE
NTS PEA GRAVEL
825'
875'
925' NTS FINES
GYPSUM CEMENT
NTS PEA GRAVEL
1850'
SWL 1825'
RIVER RUN
WASHED GRAVEL
3842'

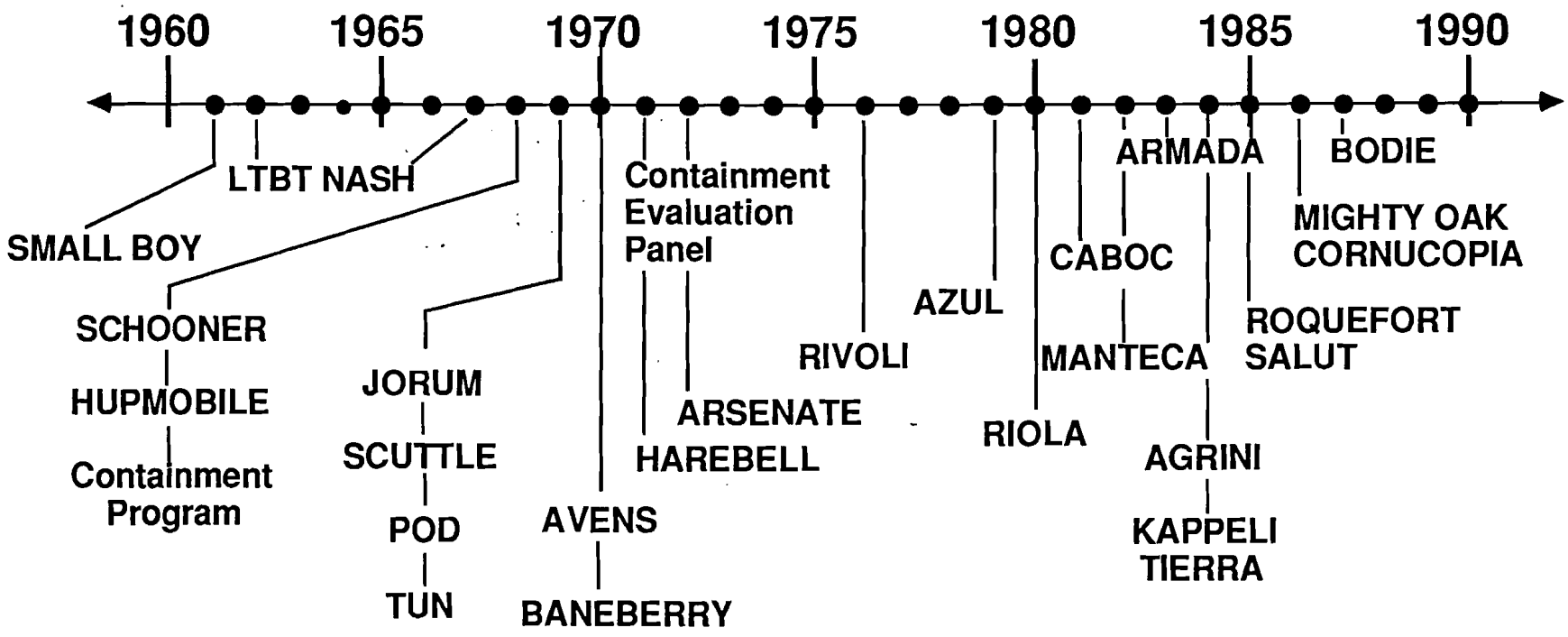
Turning Points in Containment



SCUTTLE was the last LLNL event without downhole cable gas blocks

- By the time of SCUTTLE, Bill McMaster had decided to work on the more interesting containment problems (LOS pipe closure) and asked me to be responsible for specific event-related containment
- SCUTTLE involved a small early release of radioactivity (210 Ci beginning at H + 5 minutes)
- Harry Reynolds called me that afternoon and asked why a release had occurred
- I reminded him of a memo I had sent him several weeks earlier suggesting that downhole cable gas blocks were essential

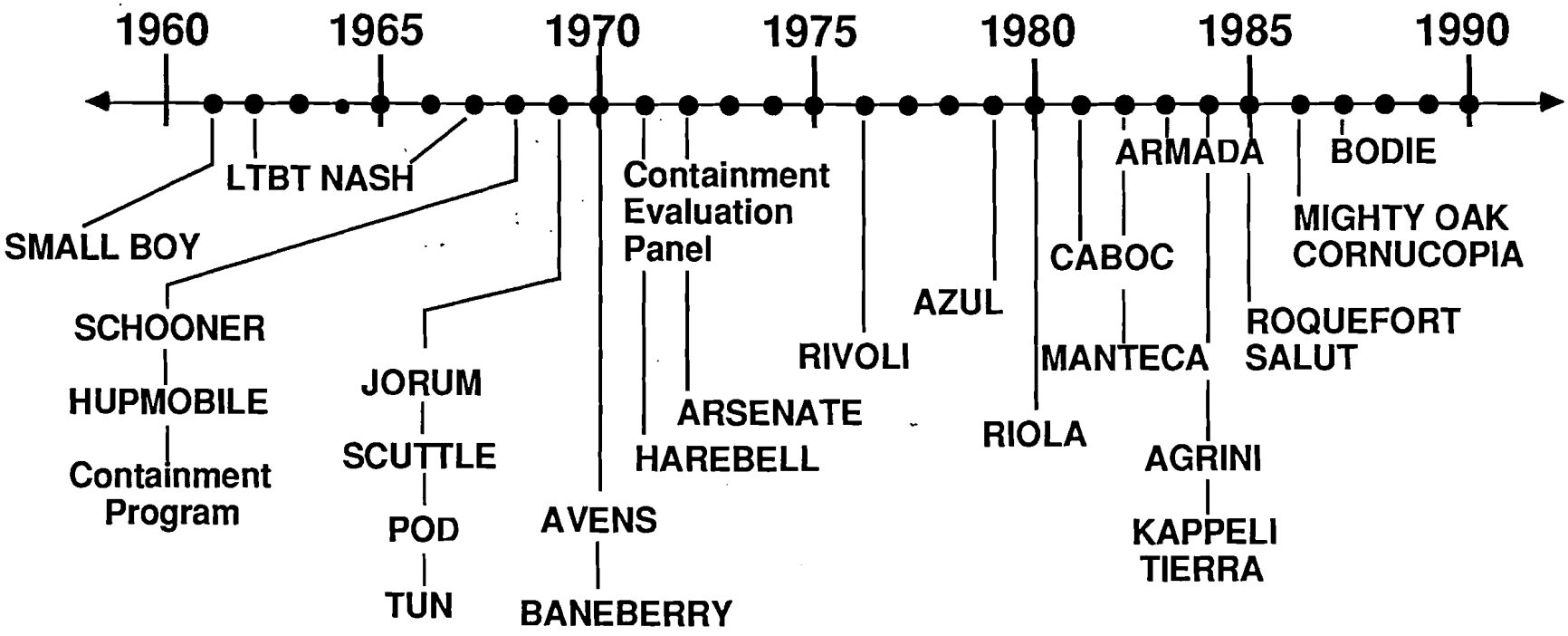
Turning Points in Containment



POD was the first event to contain a coal-tar epoxy stemming platform

- It had been observed that some events involved stemming loss after detonation
- Complete or partial stemming loss was believed to be a significant threat to containment
- It was also recognized that most event cavities could hold all of the stemming

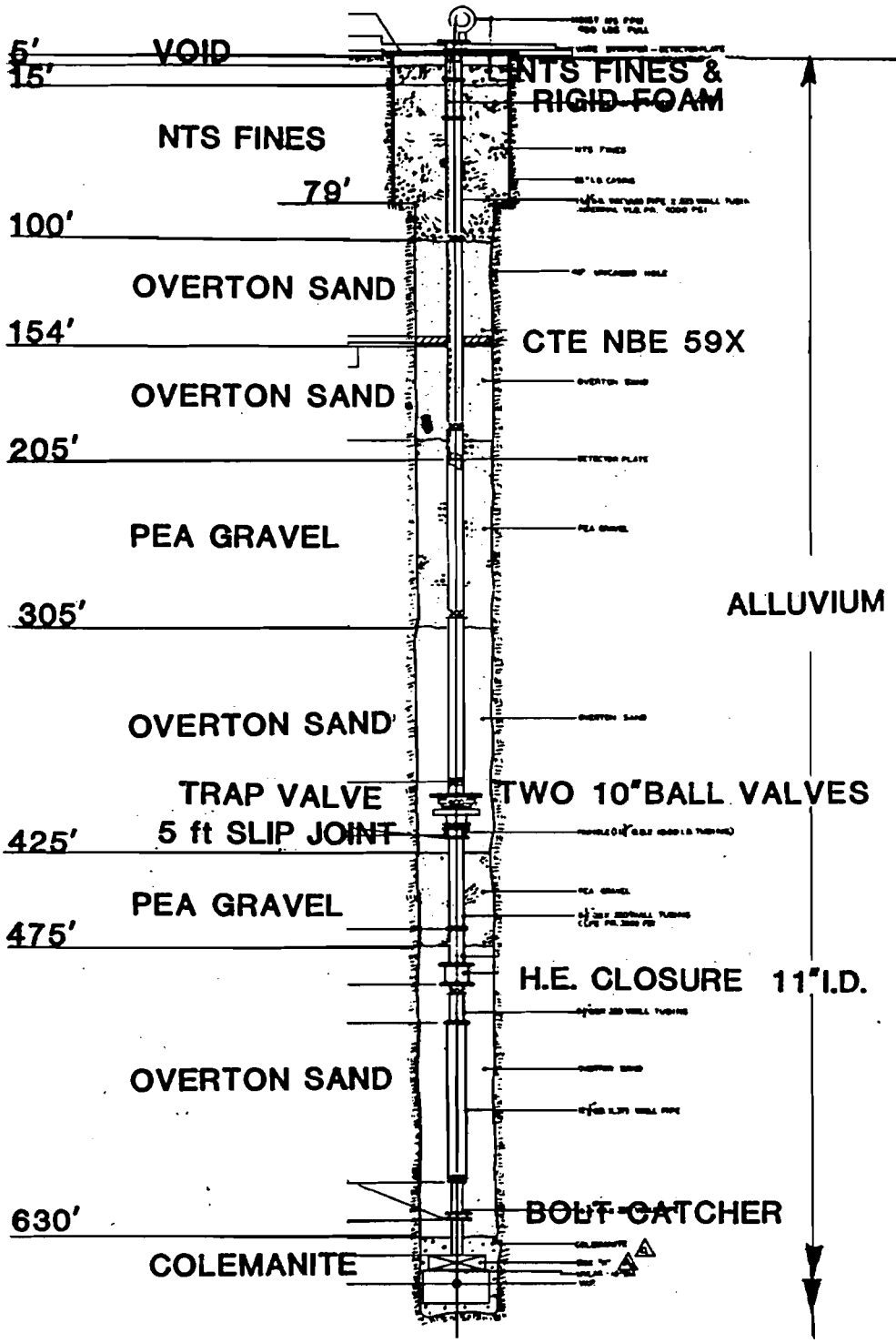
Turning Points in Containment



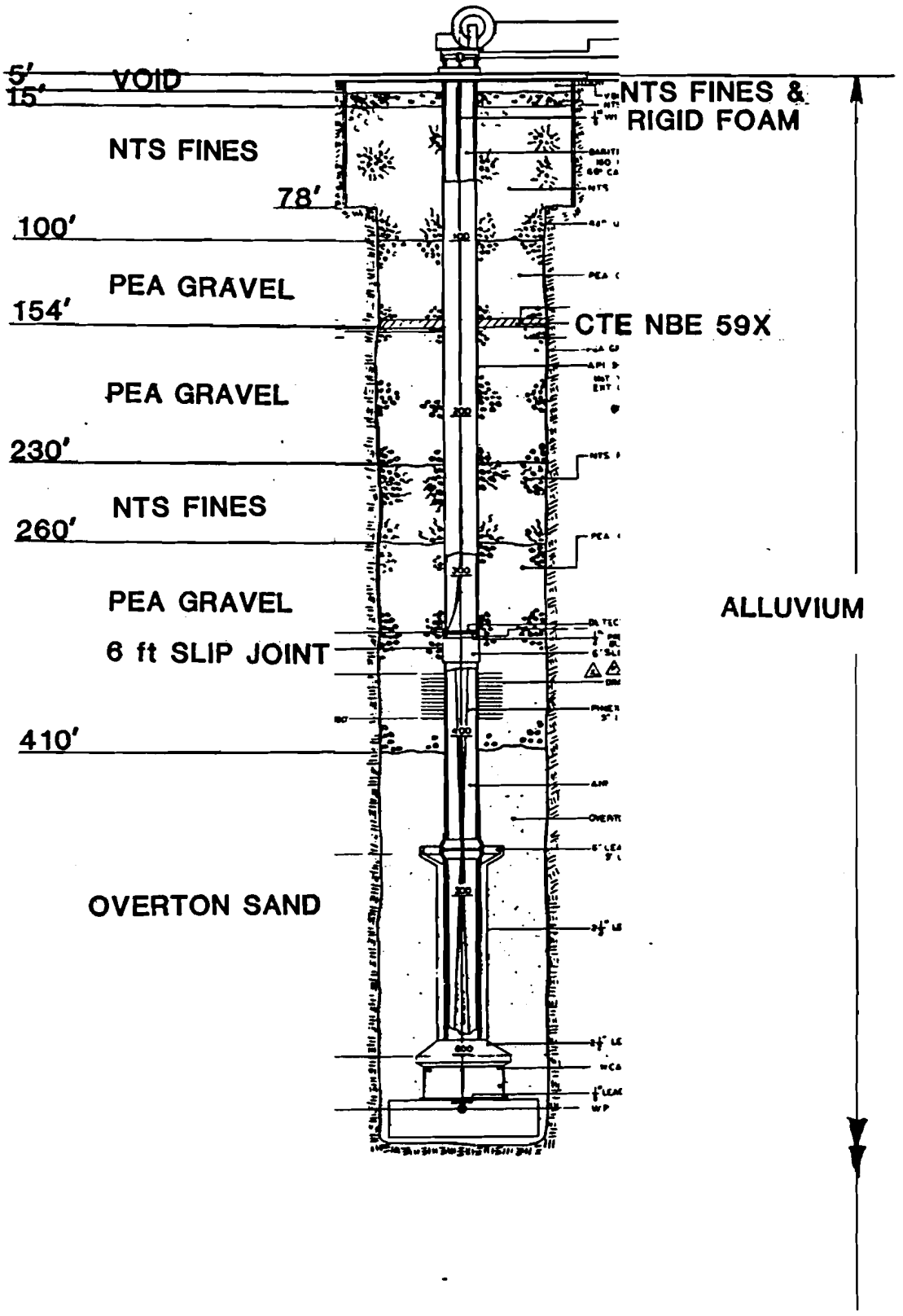
The TUN event posed a serious threat to the stemming column

- A pressure of ~ 15 psia was observed in the stemming column at approximately half a DOB
- Radioactivity was detected in the ground zero (GZ) area at H + 1 minute

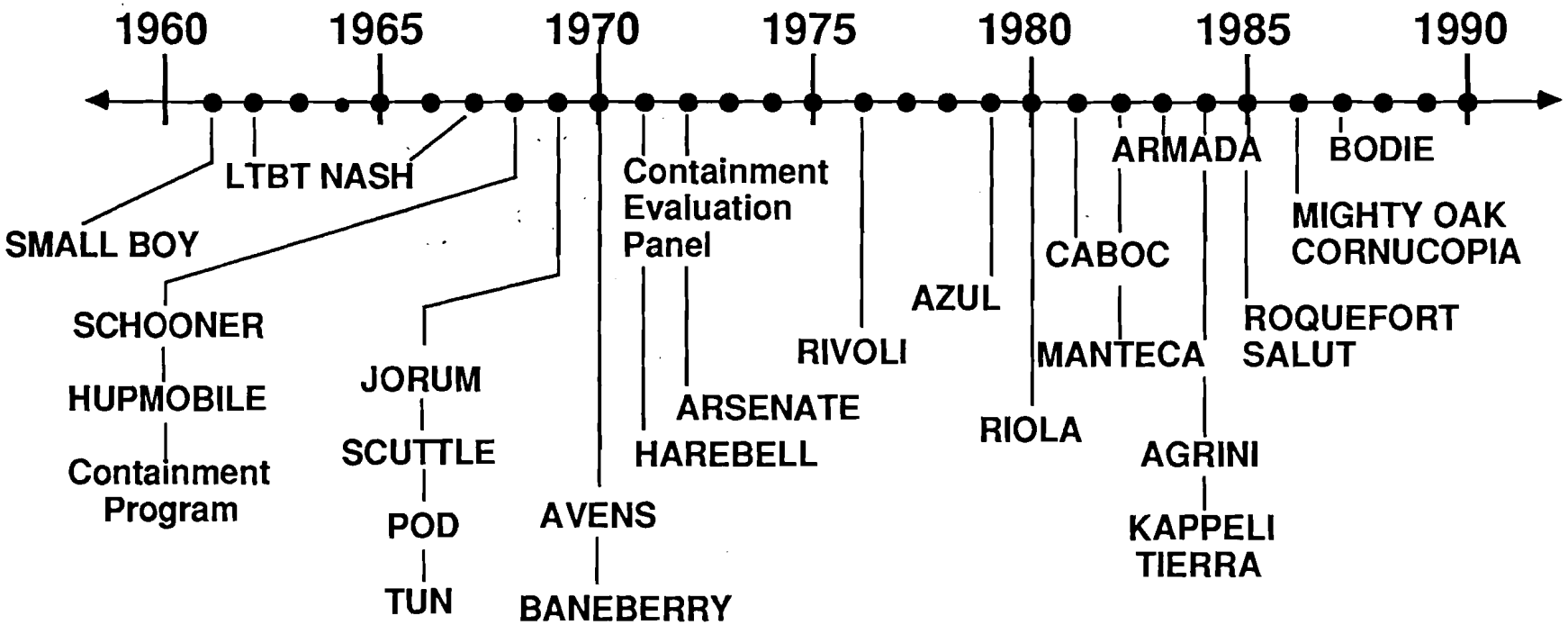
TUN No 1


5'
VOID
15'
NTS FINES & RIGID FOAM
NTS FINES
79'
100'
OVERTON SAND
154'
CTE NBE 59X
OVERTON SAND
205'
PEA GRAVEL
305'
ALLUVIUM
OVERTON SAND
TRAP VALVE
TWO 10"BALL VALVES
425'
5 ft SLIP JOINT
PEA GRAVEL
475'
H.E. CLOSURE 11"I.D.
OVERTON SAND
630'
BOLT CATCHER
COLEMANITE

TUN No 2


5'
15'
VOID
NTS FINES
78'
100'
PEA GRAVEL
154'
PEA GRAVEL
230'
NTS FINES
260'
PEA GRAVEL
6 ft SLIP JOINT
410'
OVERTON SAND
NTS FINES &
RIGID FOAM
CTE NBE 59X
ALLUVIUM

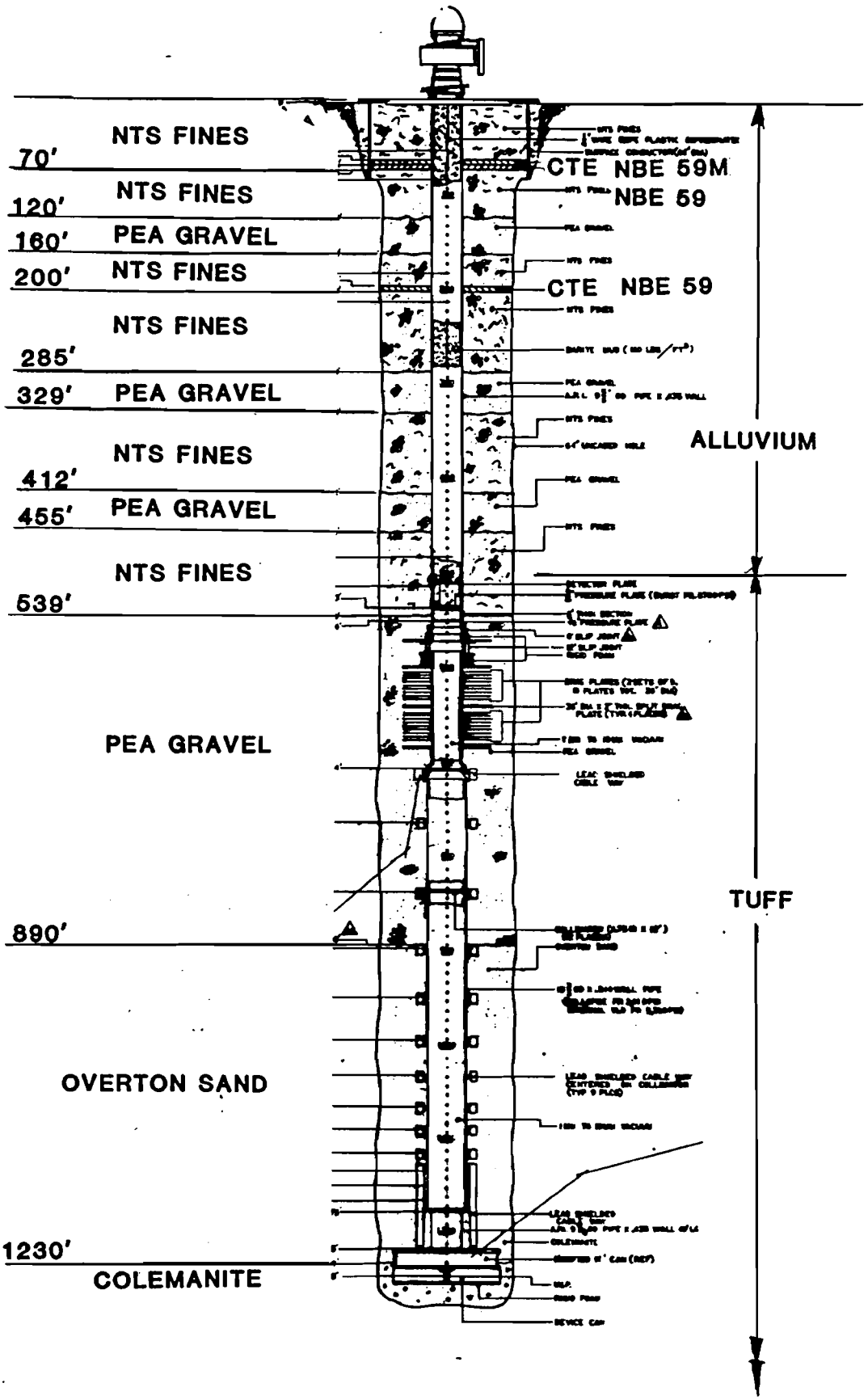
Turning Points in Containment



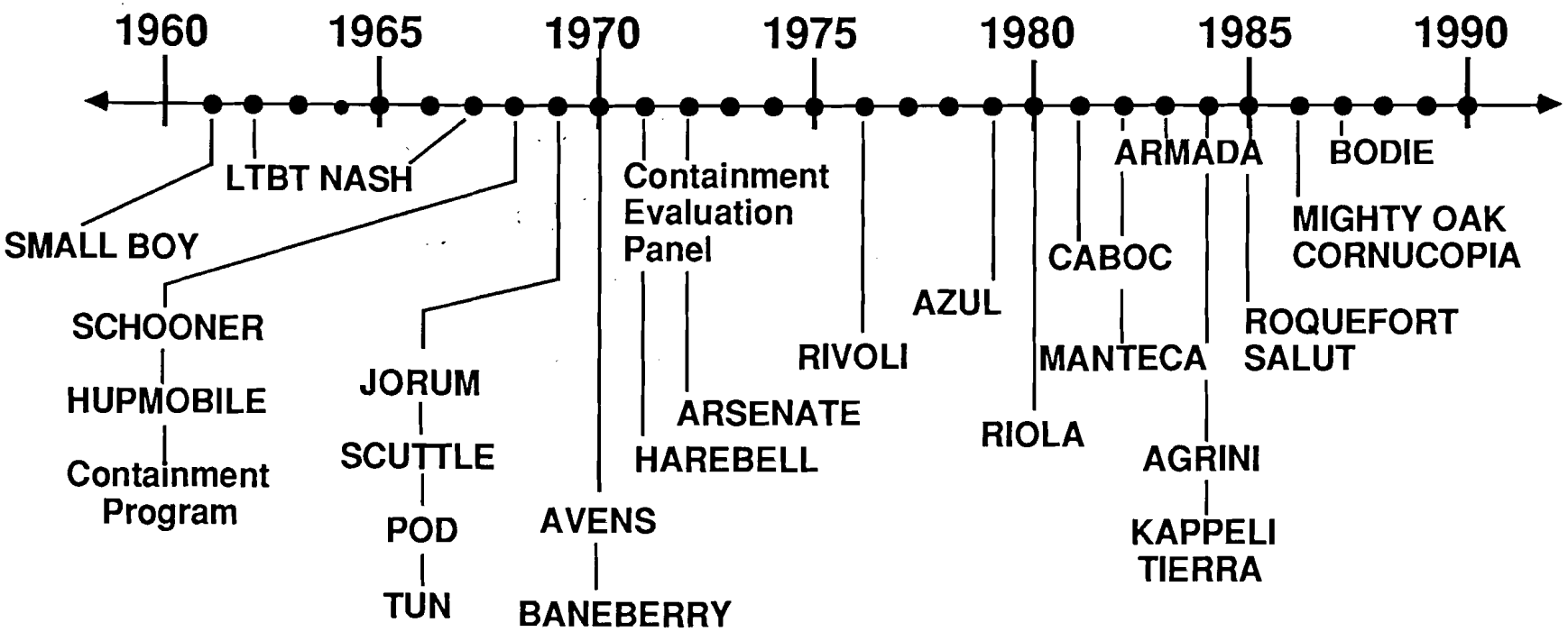
AVENS illustrated a new geologic problem

- A new emplacement hole 560 ft from an AVENS site contained radioactivity.
- A study by John Rambo suggests that permeable fractures were formed between layers having different density and velocity.

AVENS (ANDORRE) U 9 ITS T28



Turning Points in Containment



On December 18th 1970, the BANEBERRY event occurred

- A dynamic release of steam and radioactive debris began at about 3-1/2 min
- The release continued for 2 hr, venting an estimated total of 6.7×10^6 Ci into the atmosphere
- The radioactive cloud was tracked as far as the Canadian border

BANEBERRY

The BANEBERRY event of 12/18/70 resulted in a major release of radioactive material and had wide repercussions.

BANEBERRY was apparently caused by an unusual and not understood geologic setting. A comprehensive investigation was conducted; additional studies went on several years.

The CEP was formed and charged with conducting a thorough, formal review of each proposed test.

A marked increase in containment efforts resulted, especially in geology and material properties. A full evaluation is now conducted before each test.

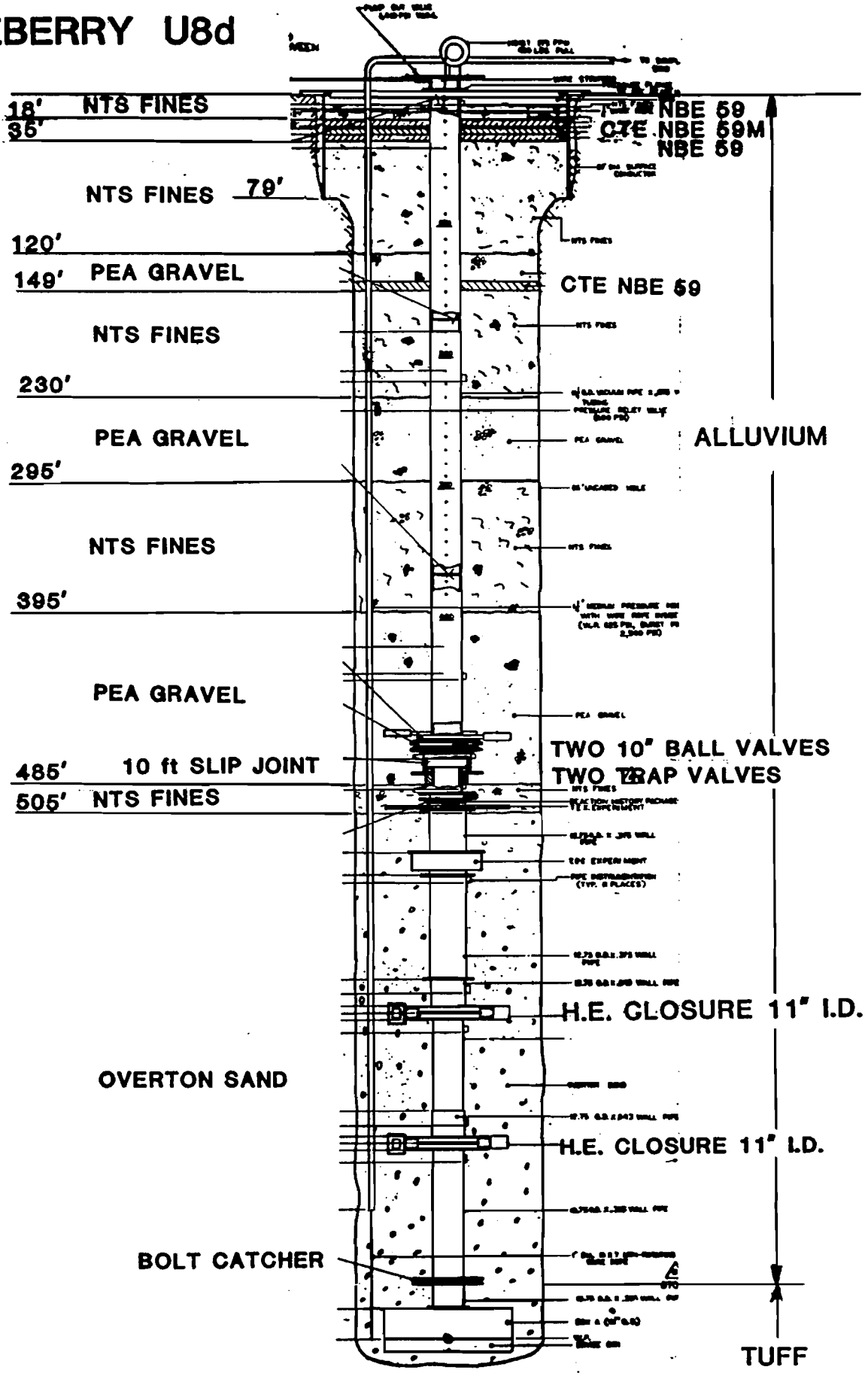
Containment concerns no longer take a backseat to operational and scheduling pressures, and more attention is paid to engineered features.

BANEBERRY had a significant impact on testing

- No tests were conducted for six months
- The Test Evaluation Panel (TEP) was replaced by the Containment Evaluation Panel (CEP) with Jim Carothers as the chairman
- The objective of the CEP was to ensure "satisfactory containment"

BANEBERRY U8d

22



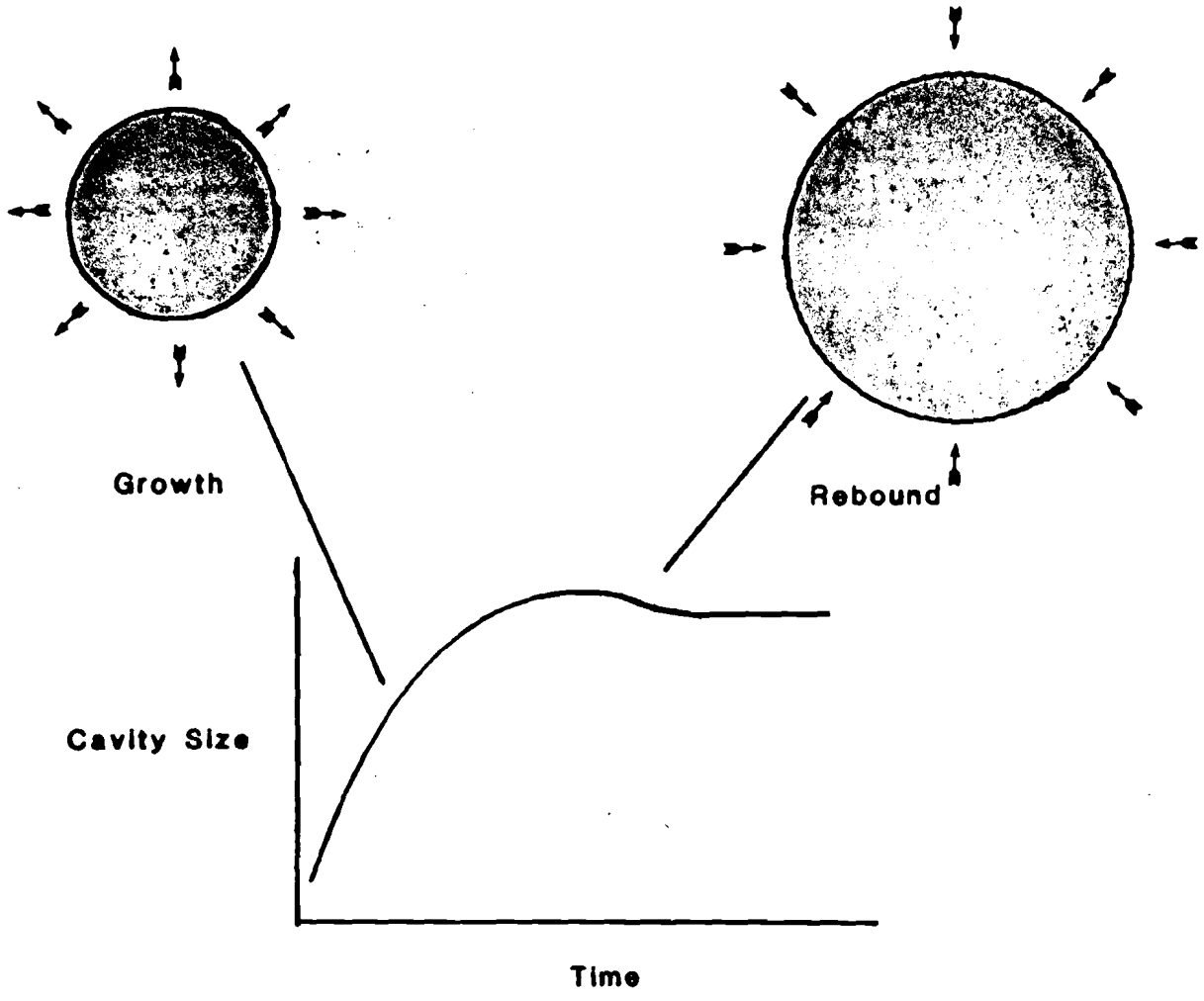
Key questions are:

- Why did BANEBERRY vent?
- Why do other events contain ?

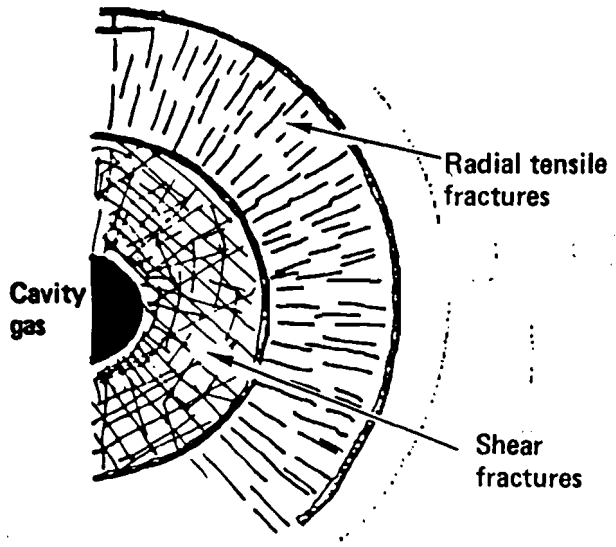
Events are thought to contain

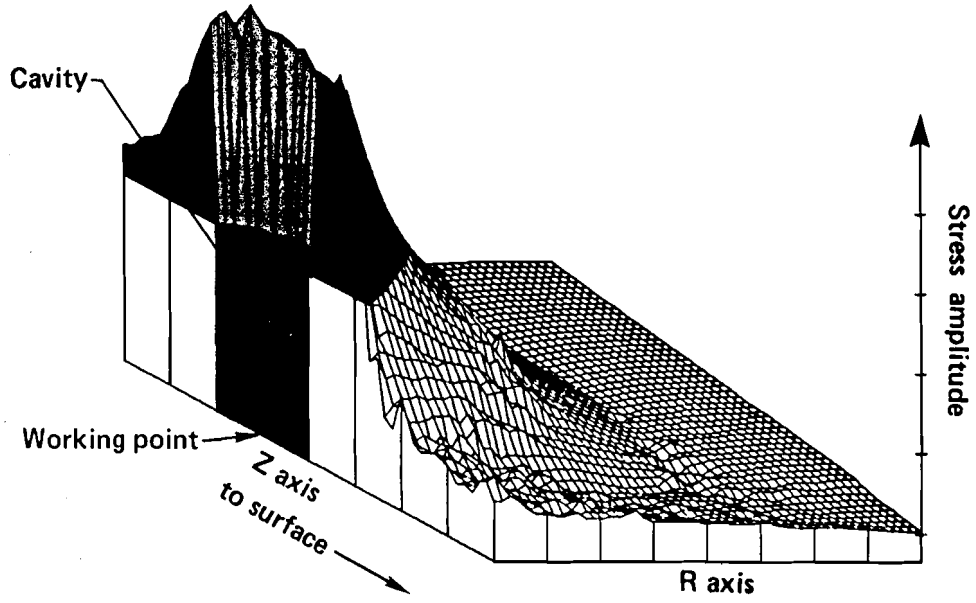
because....

The "Containment Cage" concept, residual stress higher than cavity pressure, depends on rebound of the cavity.



A hoop stress forms around the cavity sealing potential cracks...





...and containing radioactive gases within the cavity

BANEBERRY?

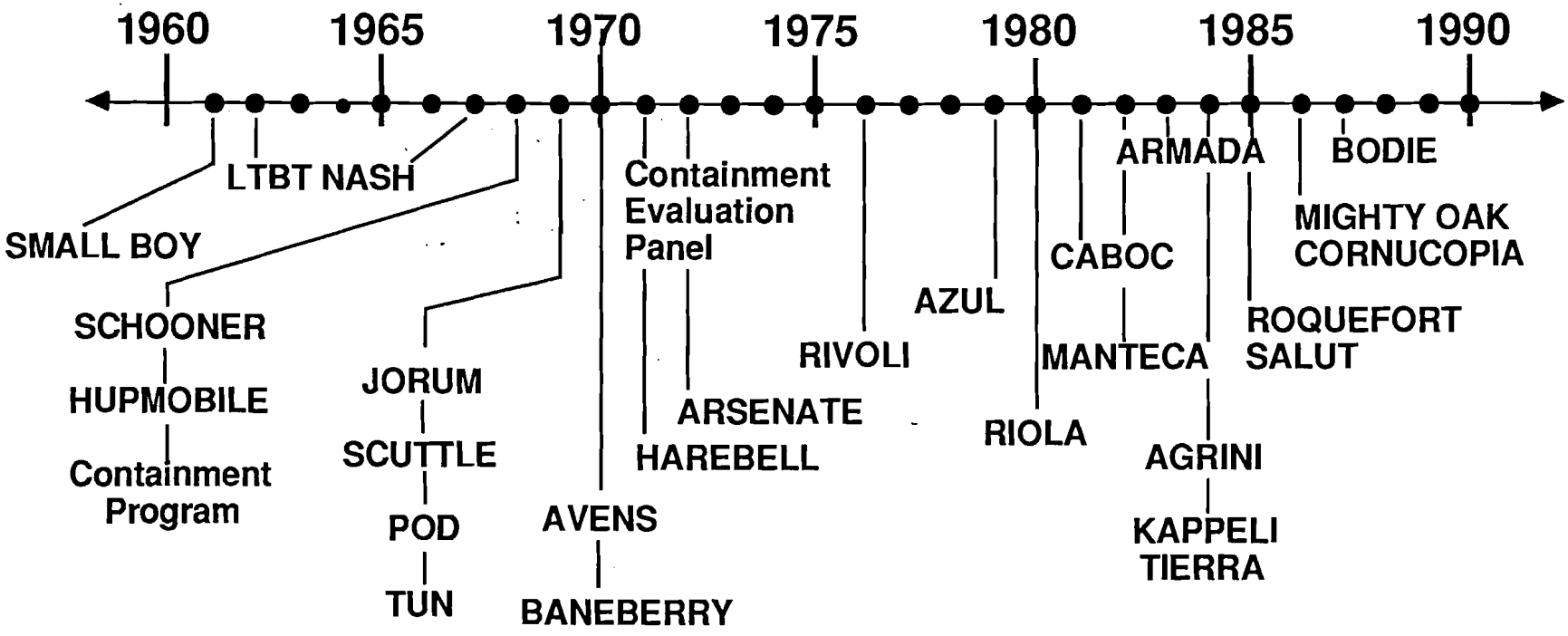
A BANEBERRY calculation

indicates an inadequate residual stress

resulting from weak material

near the cavity (saturated clay).

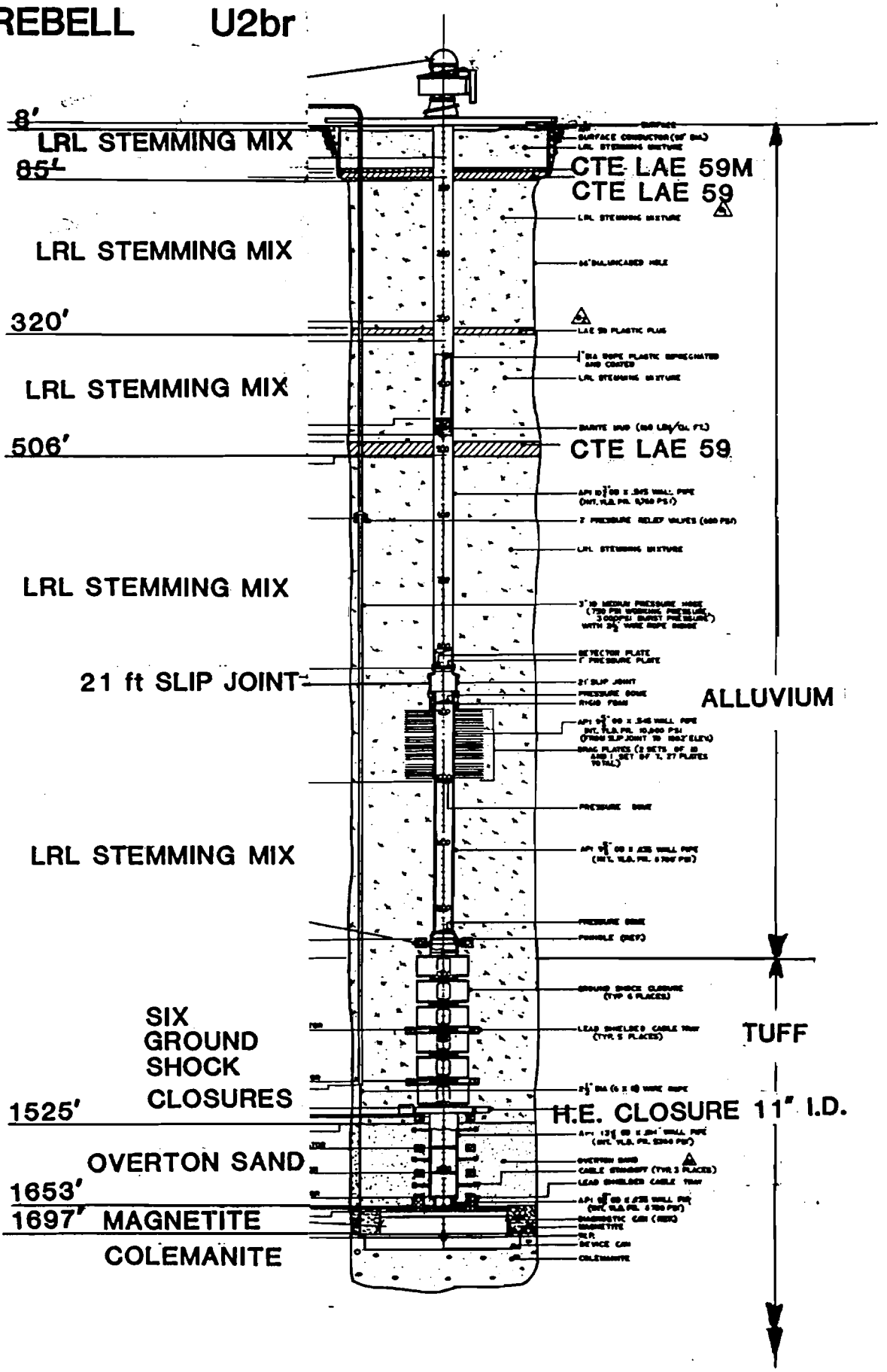
Turning Points in Containment

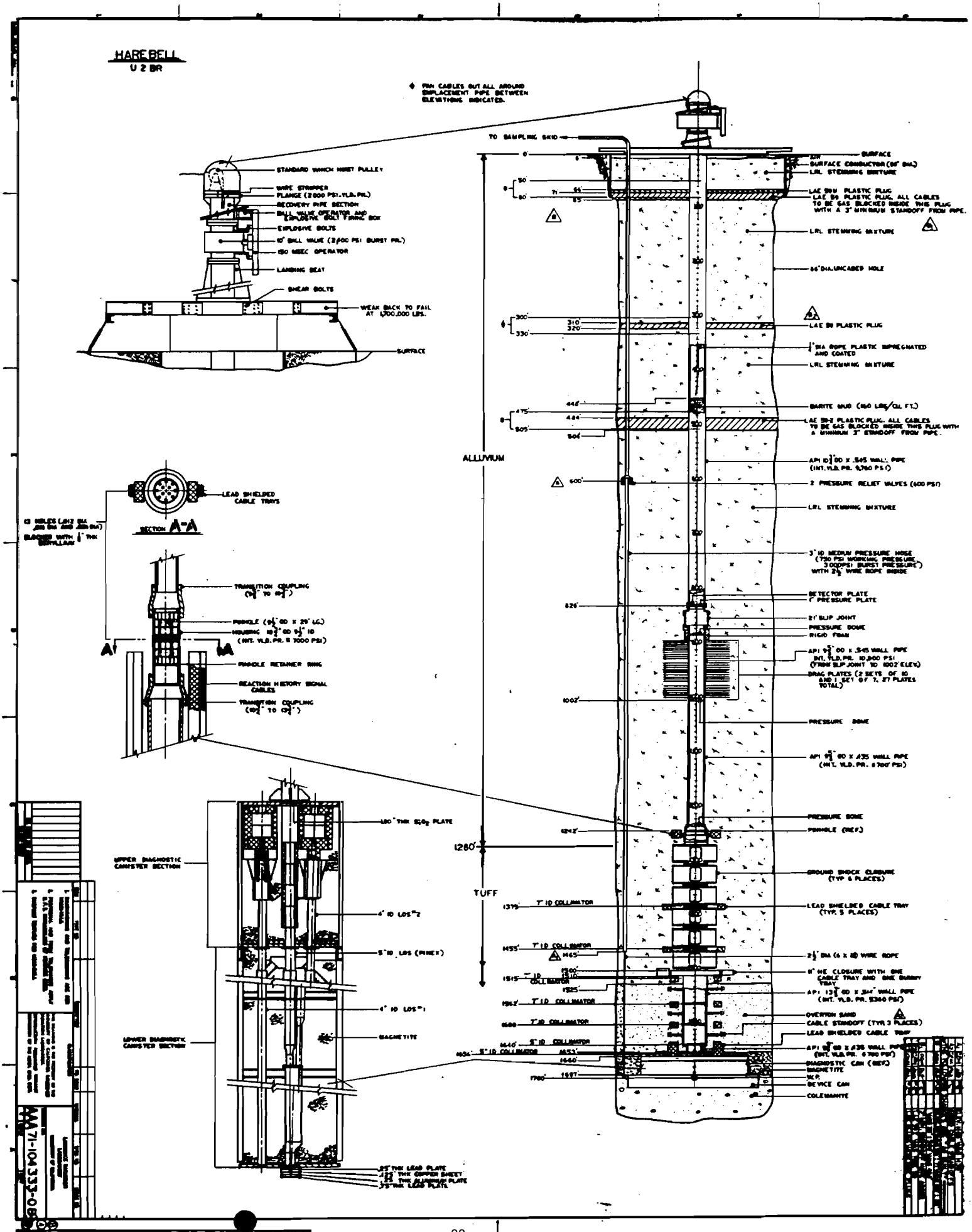


HAREBELL, The first event after BANEBERRY contained new features

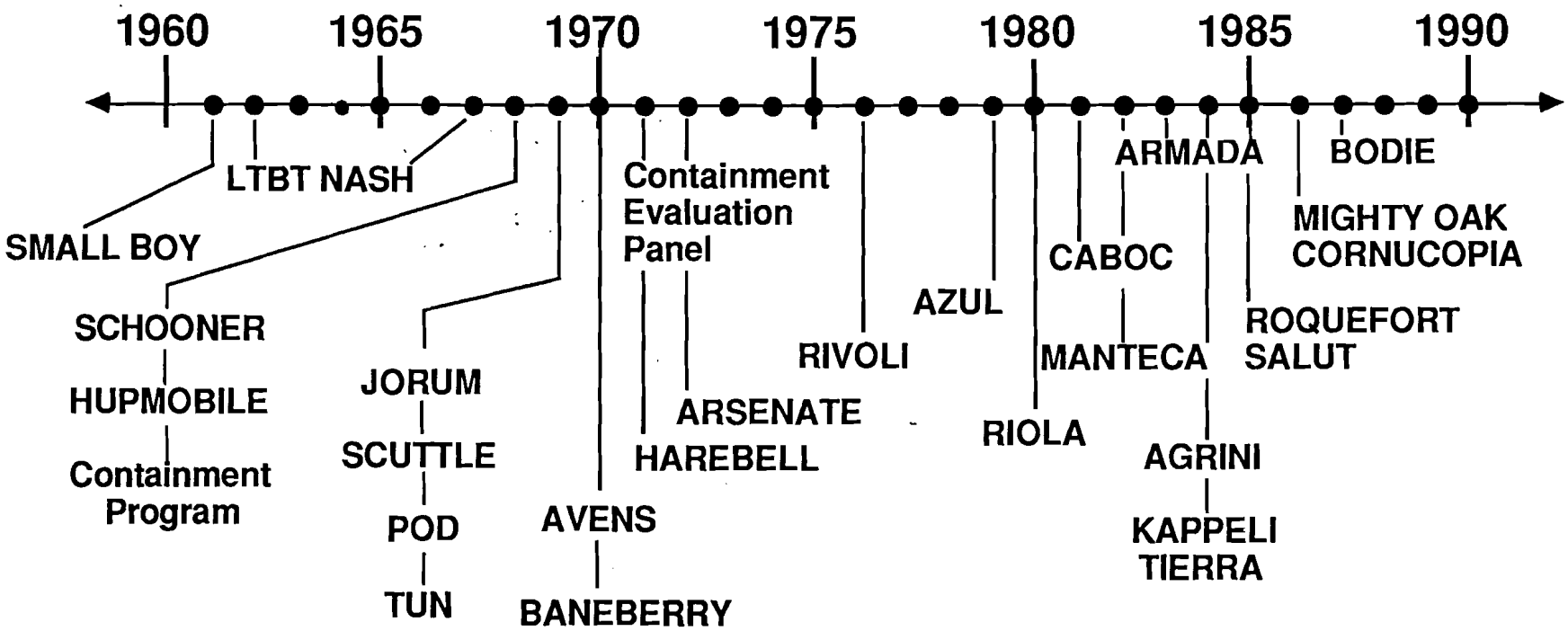
- Ground shock closure sections
- A gas tight pinhole assembly
- A CTE plug at the bottom of the surface casing
- An additional CTE plug
- Additional SDOB

HAREBELL U2br



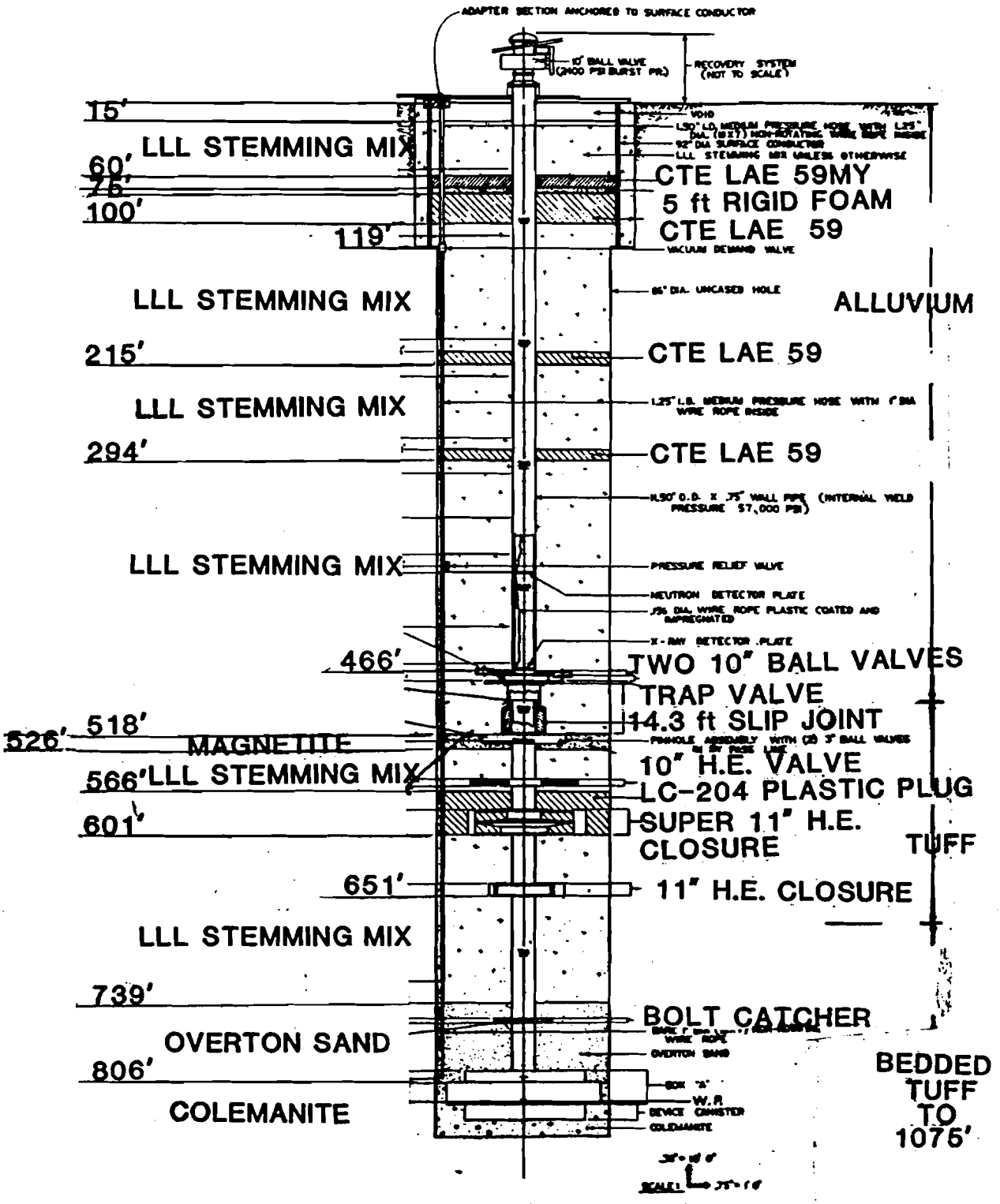

HARE BELL
U 2 BR
PIN CABLES OUT ALL AROUND DISPLACEMENT PIPE BETWEEN ELEVATIONS INDICATED.
TO SAMPLING SKID
STANDARD WINCH HEAVY PULLEY
WIPE STRIPPER
FLANGE (2000 PSI. YLD. PR.)
RECOVERY PIPE SECTION
BALL VALVE OPERATOR AND EXPLOSIVE BOLT FIRING BOX
EXPLOSIVE BOLTS
10" BALL VALVE (2,000 PSI BURST PR.)
180 MSEC OPERATOR
LANDING SEAT
SHEAR BOLTS
WEAK BACK TO FAIL AT 1,000,000 LBS.
SURFACE
SURFACE
SURFACE CONDUCTOR (30" DIA.)
LRL STEMMING MIXTURE
LAE 8IN PLASTIC PLUG
LAE 8IN PLASTIC PLUG, ALL CABLES TO BE GAS BLOCKED INSIDE THIS PLUG WITH A 3' MINIMUM STANDOFF FROM PIPE.
LRL STEMMING MIXTURE
66" DIA UNCASED HOLE
LAE 8IN PLASTIC PLUG
DIA ROPE PLASTIC IMPREGNATED AND COATED
LRL STEMMING MIXTURE
BARITE MUD (160 LBS/CU FT.)
LAE 8IN PLASTIC PLUG. ALL CABLES TO BE GAS BLOCKED INSIDE THIS PLUG WITH A MINIMUM 3' STANDOFF FROM PIPE.
ALLUVIUM
API 10 3/4" OD X .545 WALL PIPE (INT. YLD. PR. 9,760 PSI)
2 PRESSURE RELIEF VALVES (600 PSI)
LRL STEMMING MIXTURE
3" ID MEDIUM PRESSURE HOSE (750 PSI WORKING PRESSURE 3 000PSI BURST PRESSURE) WITH 2 1/2" WIRE ROPE INSIDE
DETECTOR PLATE
1" PRESSURE PLATE
2' SLIP JOINT
PRESSURE BOMB
RIGID TRAN
API 9 5/8" OD X .545 WALL PIPE INT. YLD. PR. 10,900 PSI (FROM SLIP JOINT TO 1002' ELEV.)
DRAG PLATES (2 SETS OF 10 AND 1 SET OF 7, 27 PLATES TOTAL)
PRESSURE BOMB
API 9 5/8" OD X .435 WALL PIPE (INT. YLD. PR. 8 700 PSI)
PRESSURE BOMB
PINHOLE (REF.)
1280'
TUFF
GROUND SHOCK CLOSURE (TYP. 6 PLACES)
7" ID COLLIMATOR
LEAD SHIELDED CABLE TRAY (TYP. 5 PLACES)
7" ID COLLIMATOR
2 1/2" DIA (6 X 19) WIRE ROPE
11" ID COLLIMATOR
11" ID COLLIMATOR
API 13 3/8" OD X .514" WALL PIPE (INT. YLD. PR. 5360 PSI)
7" ID COLLIMATOR
OVERTON BAND
7" ID COLLIMATOR
CABLE STANDOFF (TYP. 3 PLACES)
9" ID COLLIMATOR
LEAD SHIELDED CABLE TRAY
9" ID COLLIMATOR
API 9 5/8" OD X .435 WALL PIPE (INT. YLD. PR. 8 700 PSI)
DIAGNOSTIC CAN (REF.)
MAGNETITE
SCP
DEVICE CAN
COLEMANITE
LEAD SHIELDED CABLE TRAYS
SECTION A-A
TRANSITION COUPLING
PINHOLE (9 5/8" OD X 29' LG.)
HOUSING
PINHOLE RETAINER RING
REACTION HISTORY SIGNAL CABLES
TRANSITION COUPLING
UPPER DIAGNOSTIC CANISTER SECTION
LOWER DIAGNOSTIC CANISTER SECTION
4" ID LOS
5" ID LOS (PINEX)
4" ID LOS
MAGNETITE
.25" THK LEAD PLATE
.12" THK GYPSUM SHEET
.75" THK ALUMINUM PLATE
.75" THK LEAD PLATE
HARE BELL "REVISED"
PICTORIAL SUMMARY AND STEMMING PLAN

Turning Points in Containment

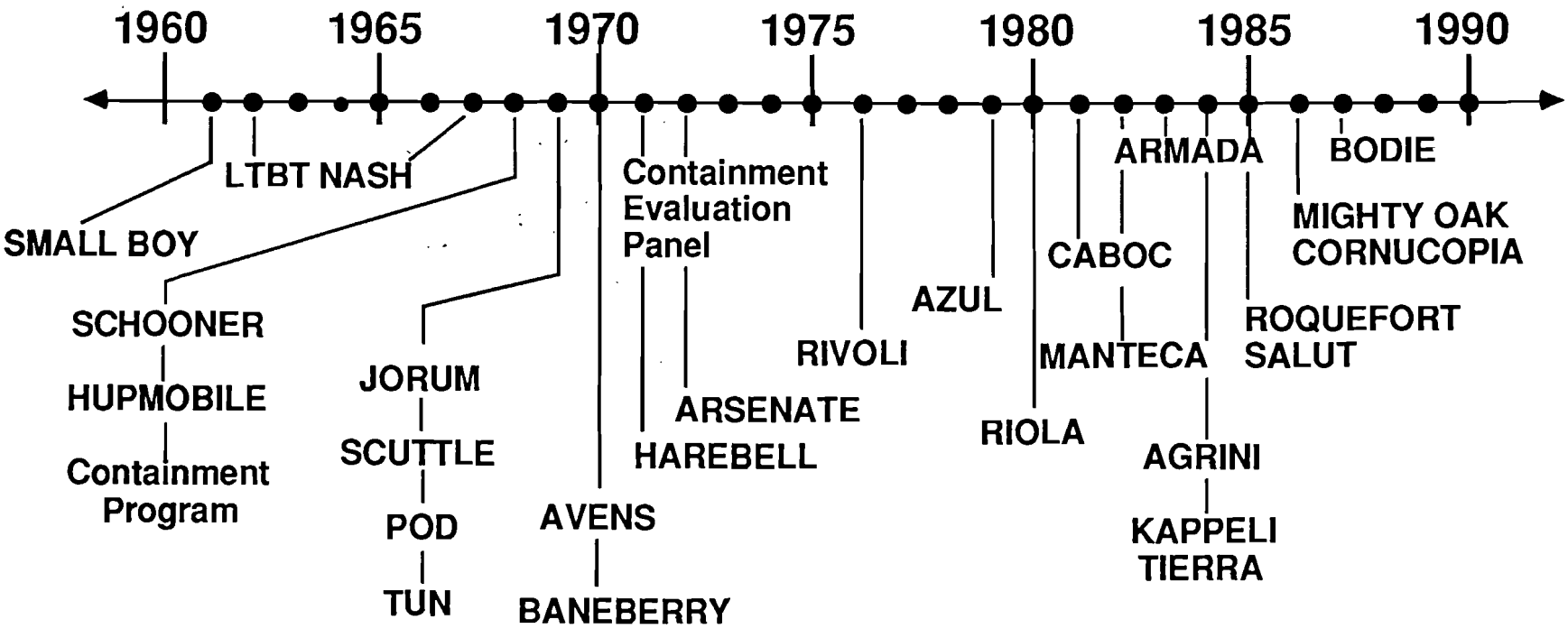


ARSENATE was the last x-ray pinex event

ARSENATE U9ci



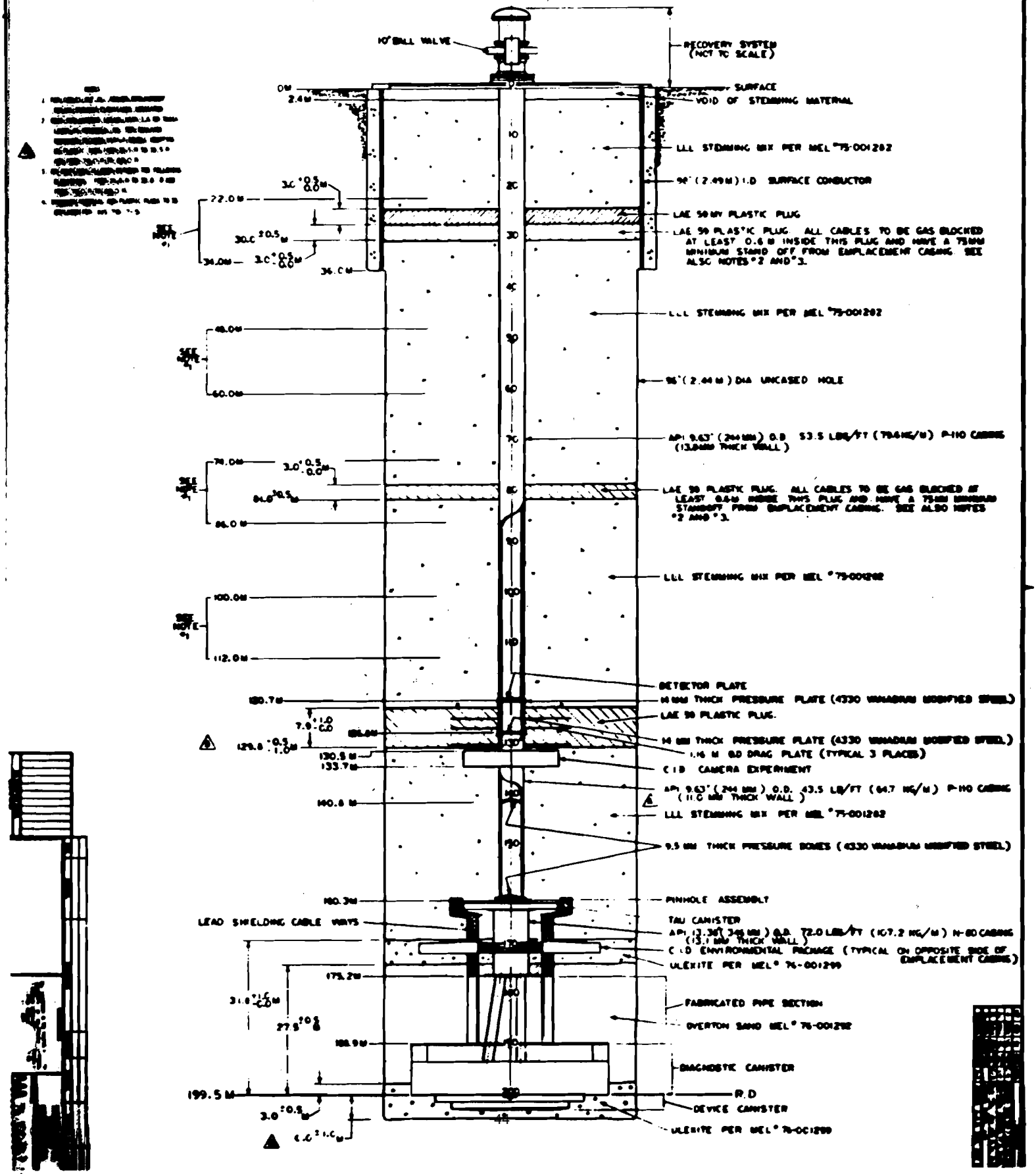
Turning Points in Containment



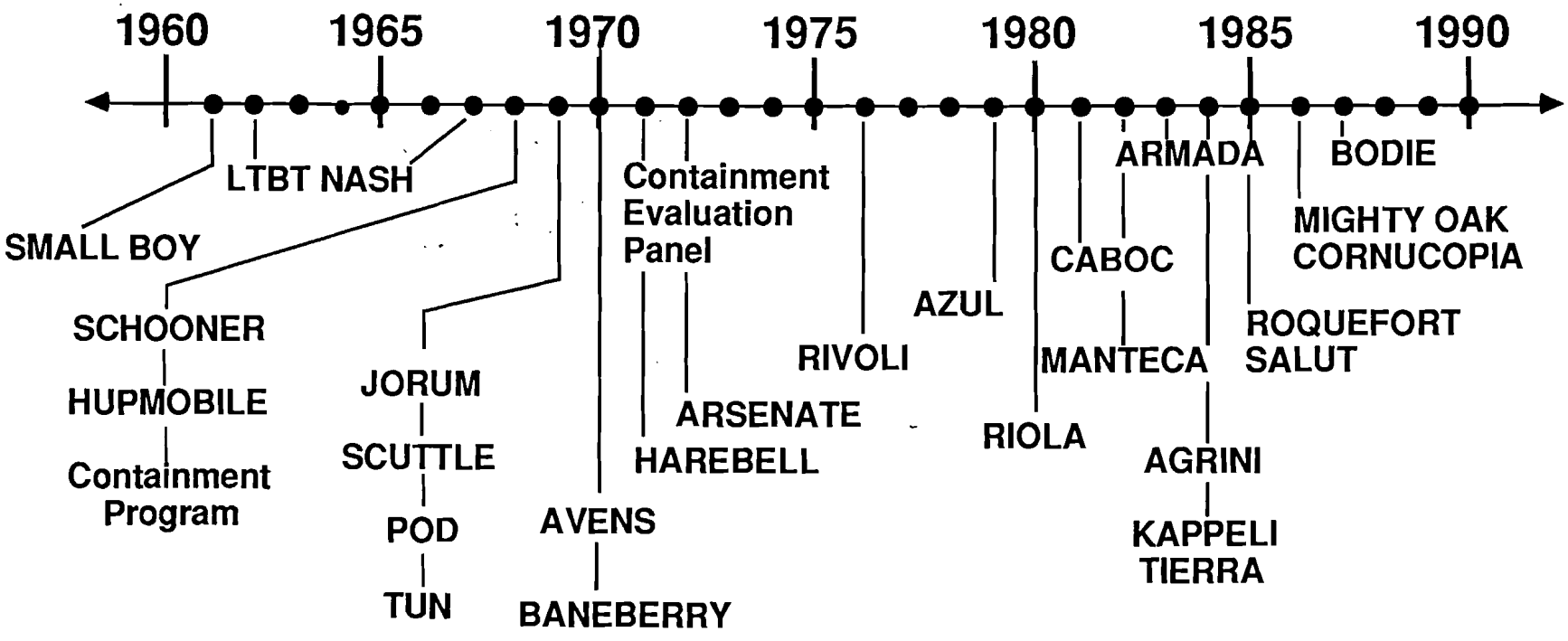
RIVOLI involved the first release of radioactivity after BANEBERRY

- Very low level radioactivity was detected near GZ
- Significant levels of radioactivity were detected immediately below the upper CTE plug
- Drill-back explorations indicated sub-surface subsidence with a standing void beneath the upper CTE plug
- Increased care was taken to block radiation deep in the hole
- A careful review of containment related diagnostics data and a special presentation to the CEP allowed testing to continue

RIVOLI
U2EG


10" BALL VALVE
RECOVERY SYSTEM (NOT TO SCALE)
SURFACE
VOID OF STEMMING MATERIAL
LLL STEMMING MIX PER MEL °75-001282
9⅝" (2.49 M) I.D SURFACE CONDUCTOR
LAE 50 MV PLASTIC PLUG
LAE 50 PLASTIC PLUG. ALL CABLES TO BE GAS BLOCKED AT LEAST 0.6 M INSIDE THIS PLUG AND HAVE A 75MM MINIMUM STAND OFF FROM EMPLACEMENT CASING. SEE ALSO NOTES °2 AND °3.
LLL STEMMING MIX PER MEL °75-001282
96" (2.44 M) DIA UNCASED HOLE
API 9.63" (244 MM) O.D. 53.5 LBS/FT (79.6 KG/M) P-110 CASING (13.0MM THICK WALL)
LAE 50 PLASTIC PLUG. ALL CABLES TO BE GAS BLOCKED AT LEAST 0.6 M INSIDE THIS PLUG AND HAVE A 75MM MINIMUM STANDOFF FROM EMPLACEMENT CASING. SEE ALSO NOTES °2 AND °3.
LLL STEMMING MIX PER MEL °75-001282
DETECTOR PLATE
50 MM THICK PRESSURE PLATE (4330 VANADIUM MODIFIED STEEL)
LAE 50 PLASTIC PLUG.
50 MM THICK PRESSURE PLATE (4330 VANADIUM MODIFIED STEEL)
1.16 M O.D DRAG PLATE (TYPICAL 3 PLACES)
C I D CAMERA EXPERIMENT
API 9.63" (244 MM) O.D. 43.5 LB/FT (64.7 KG/M) P-110 CASING (11.0 MM THICK WALL)
LLL STEMMING MIX PER MEL °75-001282
9.5 MM THICK PRESSURE BOXES (4330 VANADIUM MODIFIED STEEL)
PINHOLE ASSEMBLY
LEAD SHIELDING CABLE WAYS
TAU CANISTER
API 13.38" 340 MM) O.D. 72.0 LBS/FT (107.2 KG/M) N-80 CASING (13.1 MM THICK WALL)
C I D ENVIRONMENTAL PACKAGE (TYPICAL ON OPPOSITE SIDE OF EMPLACEMENT CASING)
ULEXITE PER MEL° 76-001299
FABRICATED PIPE SECTION
OVERTON SAND MEL° 76-001282
DIAGNOSTIC CANISTER
R.D
DEVICE CANISTER
ULEXITE PER MEL° 76-001299
0M
2.4M
22.0M
30.0M
34.0M
36.0M
48.0M
60.0M
78.0M
84.0M
86.0M
100.0M
112.0M
130.7M
129.8M
130.8M
133.7M
140.8M
160.3M
175.2M
199.5M

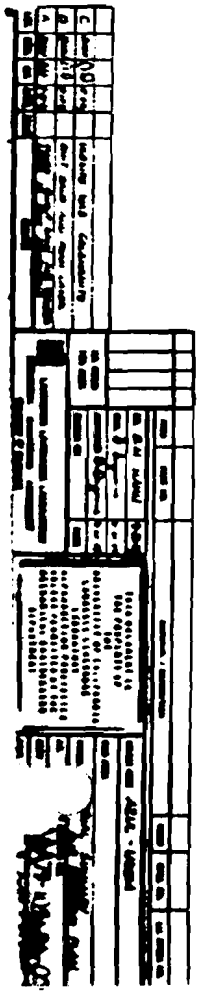
Turning Points in Containment



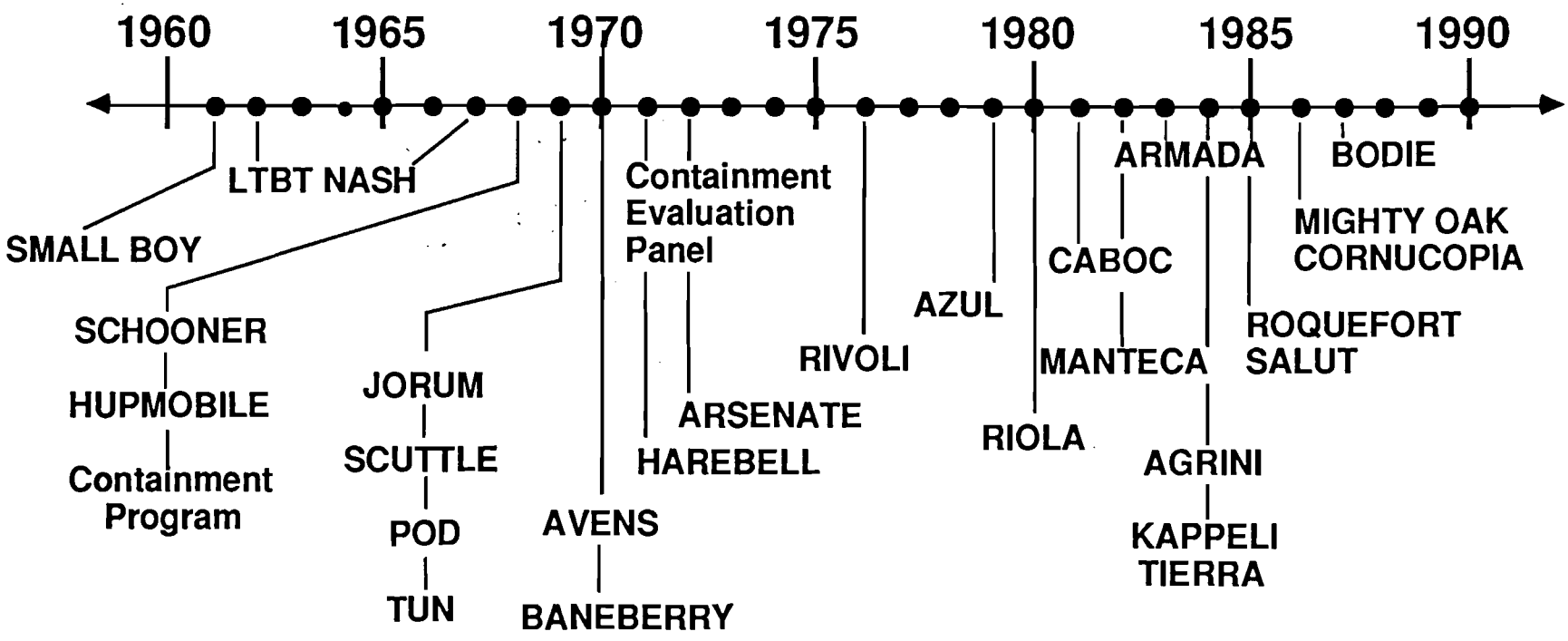
AZUL: A fines layer with cable fan-out and gasblocks was not a block to gas flow

- Gas at low pressure passed a 12 m fines layer in a few seconds
- Subsequent fan-outs were improved with wider cable spacings

AZUL
UXEM



Turning Points in Containment



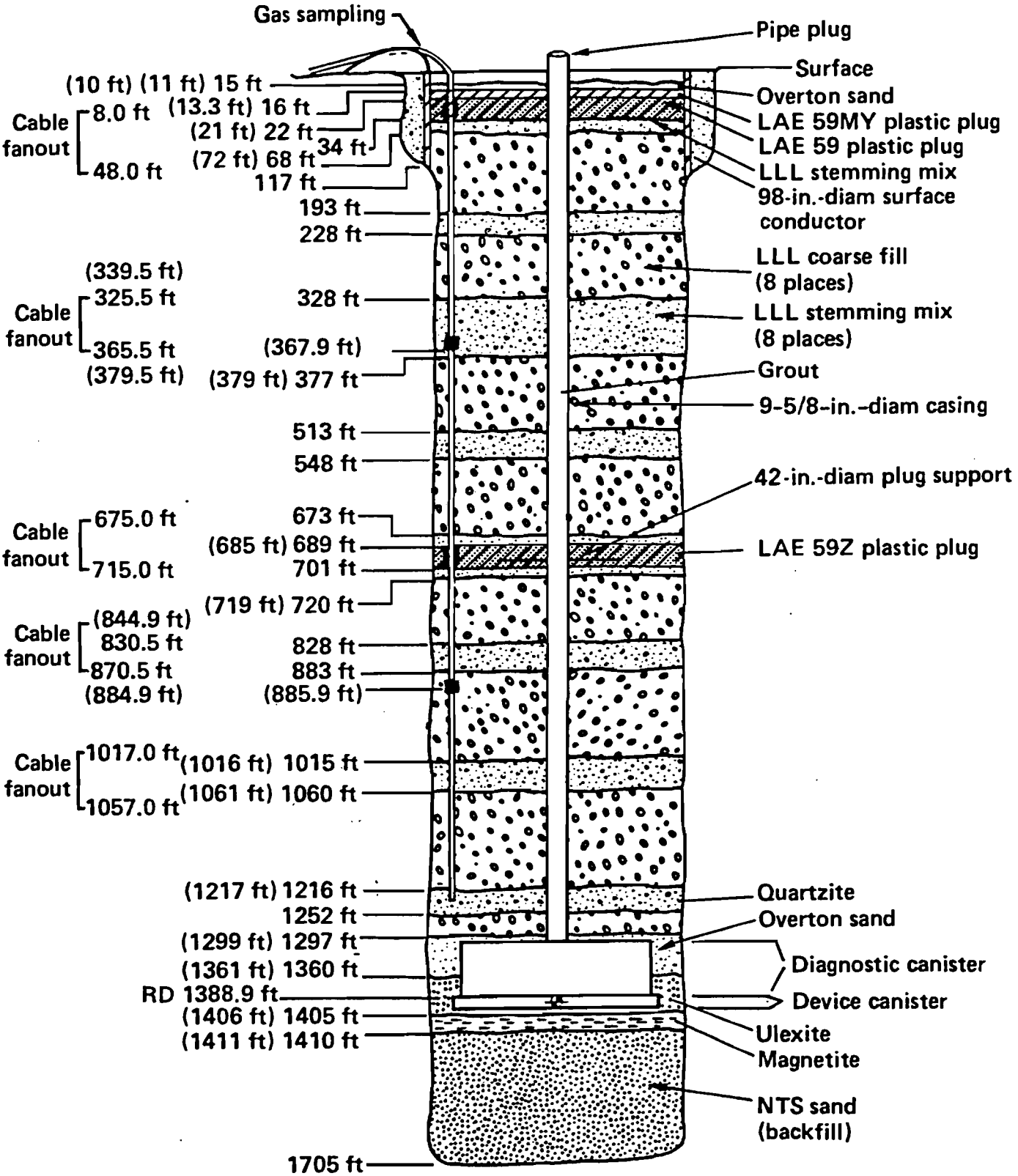
RIOLA involved a release of radioactivity which was detected off-site

- Drill back exploration and bore hole photography suggests a CTE stemming platform failed
- Tests were carried out to determine whether in place CTE was consistent with samples taken at the surface, with negative results
- An effort was instigated to find a replacement for CTE

Investigation costs were high.

There were no containment diagnostics.

RIOLA U2eq

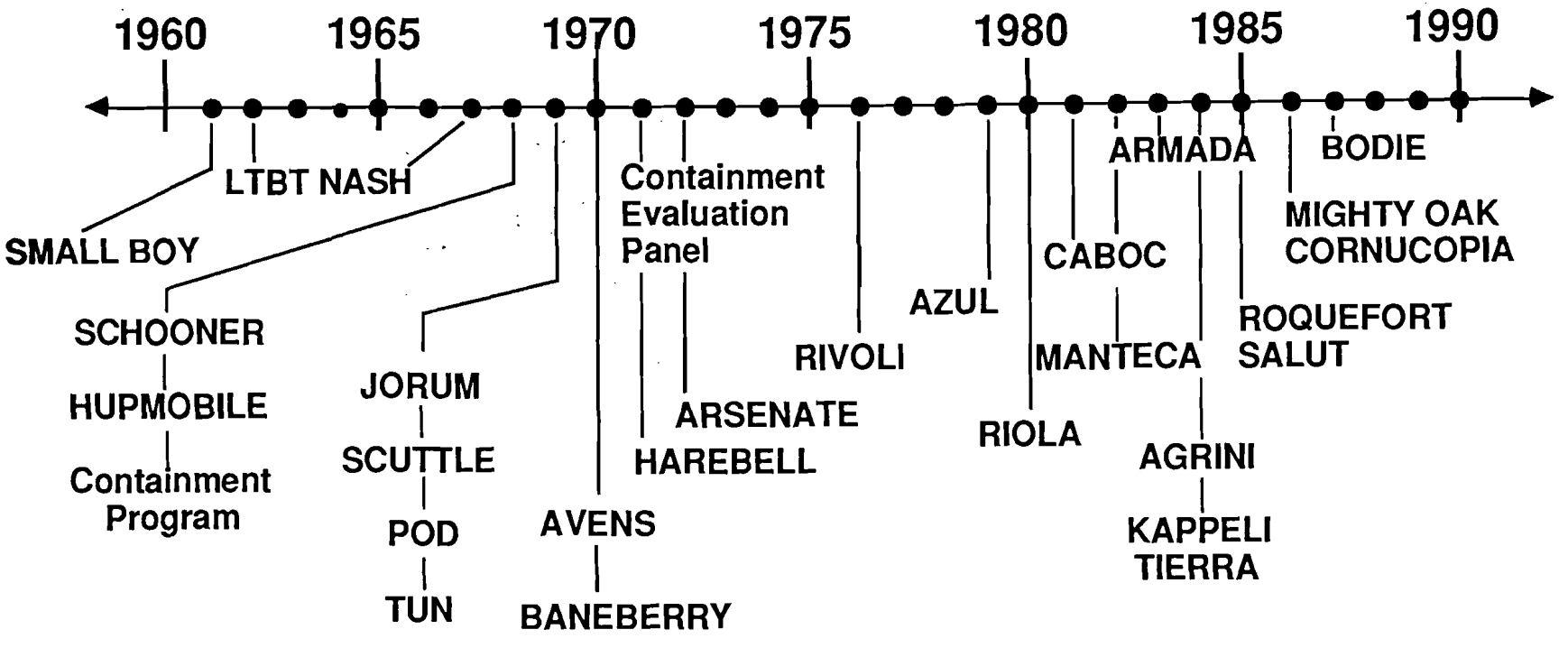


FROM UCRL-53437

We adopted an even more aggressive diagnostics philosophy

- Quality assessment diagnostics should be fielded on all events.
- Performance diagnostics should be fielded on all events
- Phenomenology measurements should be fielded when appropriate

Turning Points in Containment

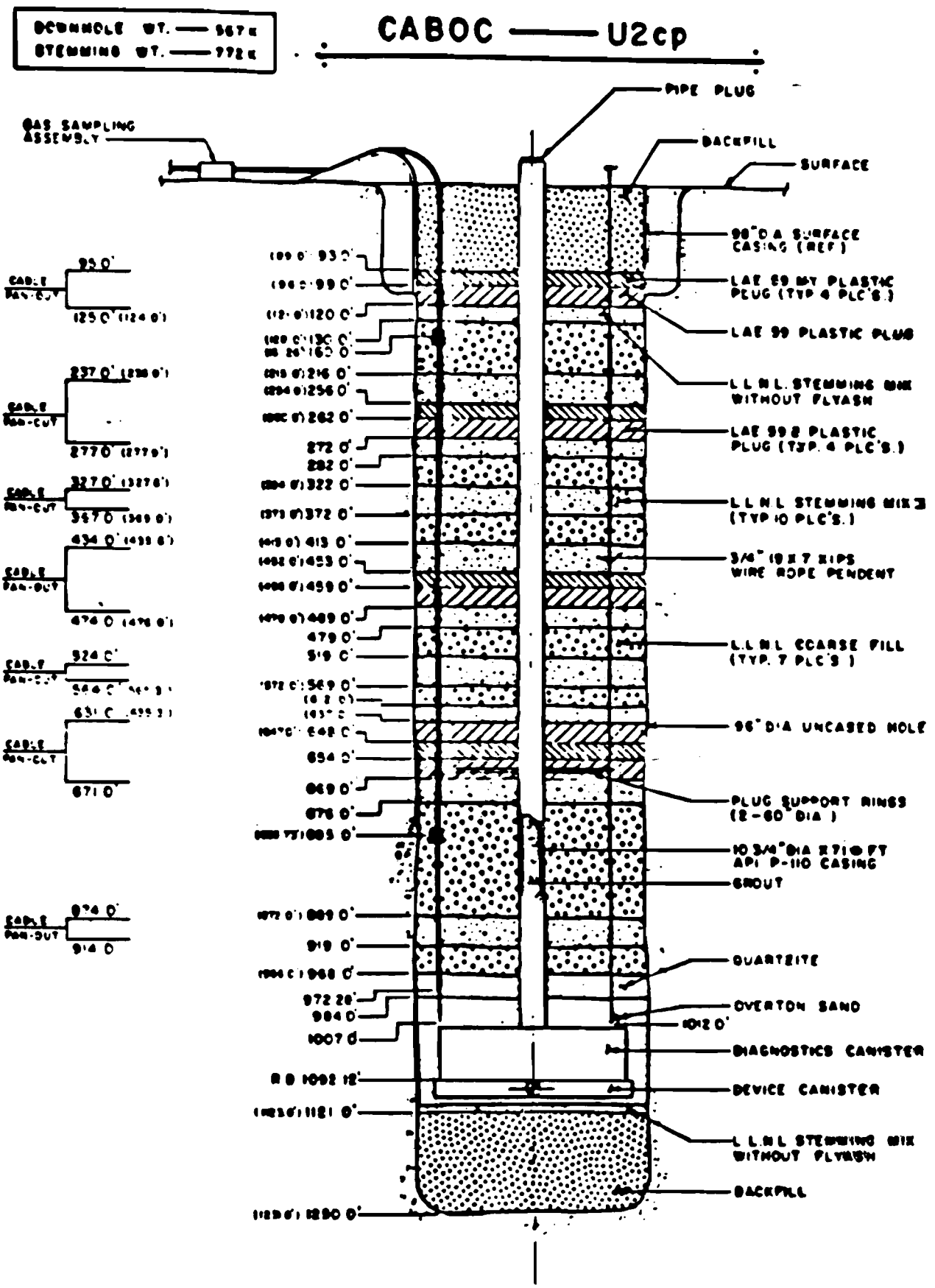


A deep plug was used for the first time on CABOC

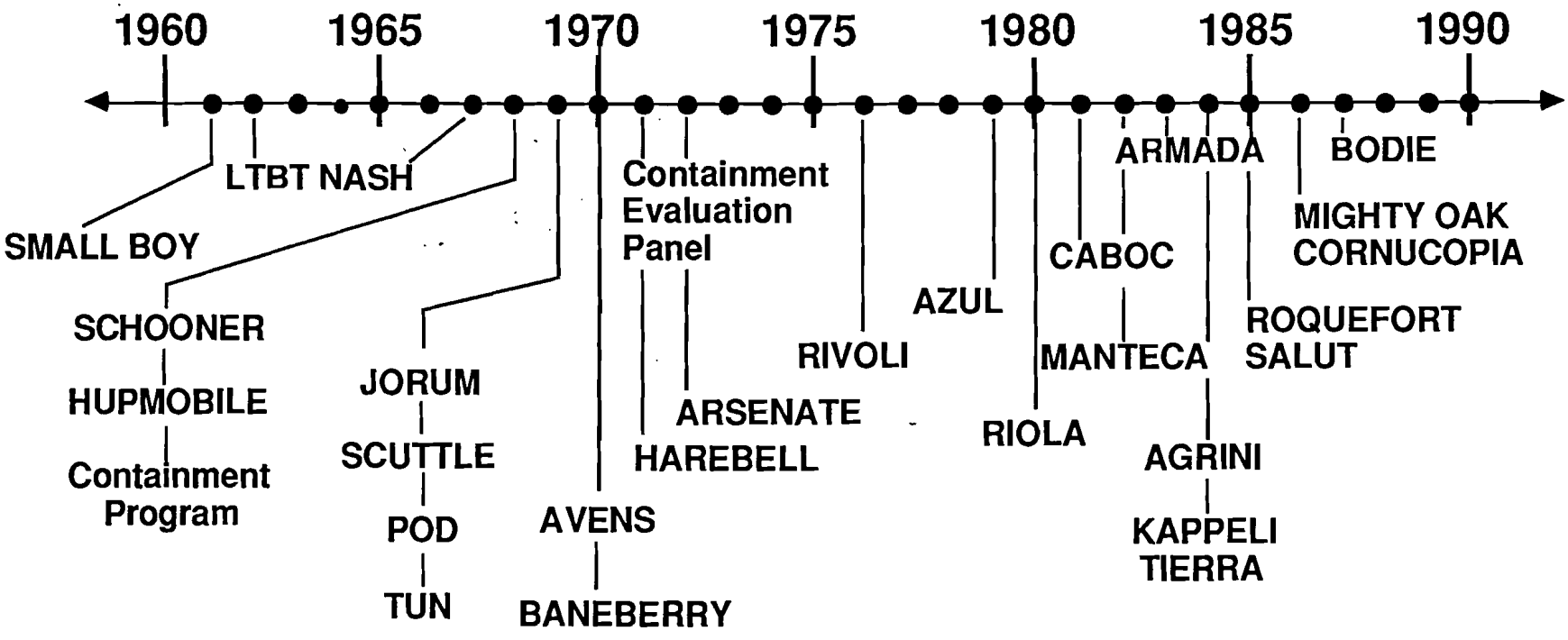
Before CABOC, radioactivity was observed well up in the stemming column in less than one minute 90% of the time

On CABOC

- Radioactivity was not observed above the deep plug
- Subsequent experience shows deep plugs to be effective about 80% of the time
- All LLNL events currently have deep plugs

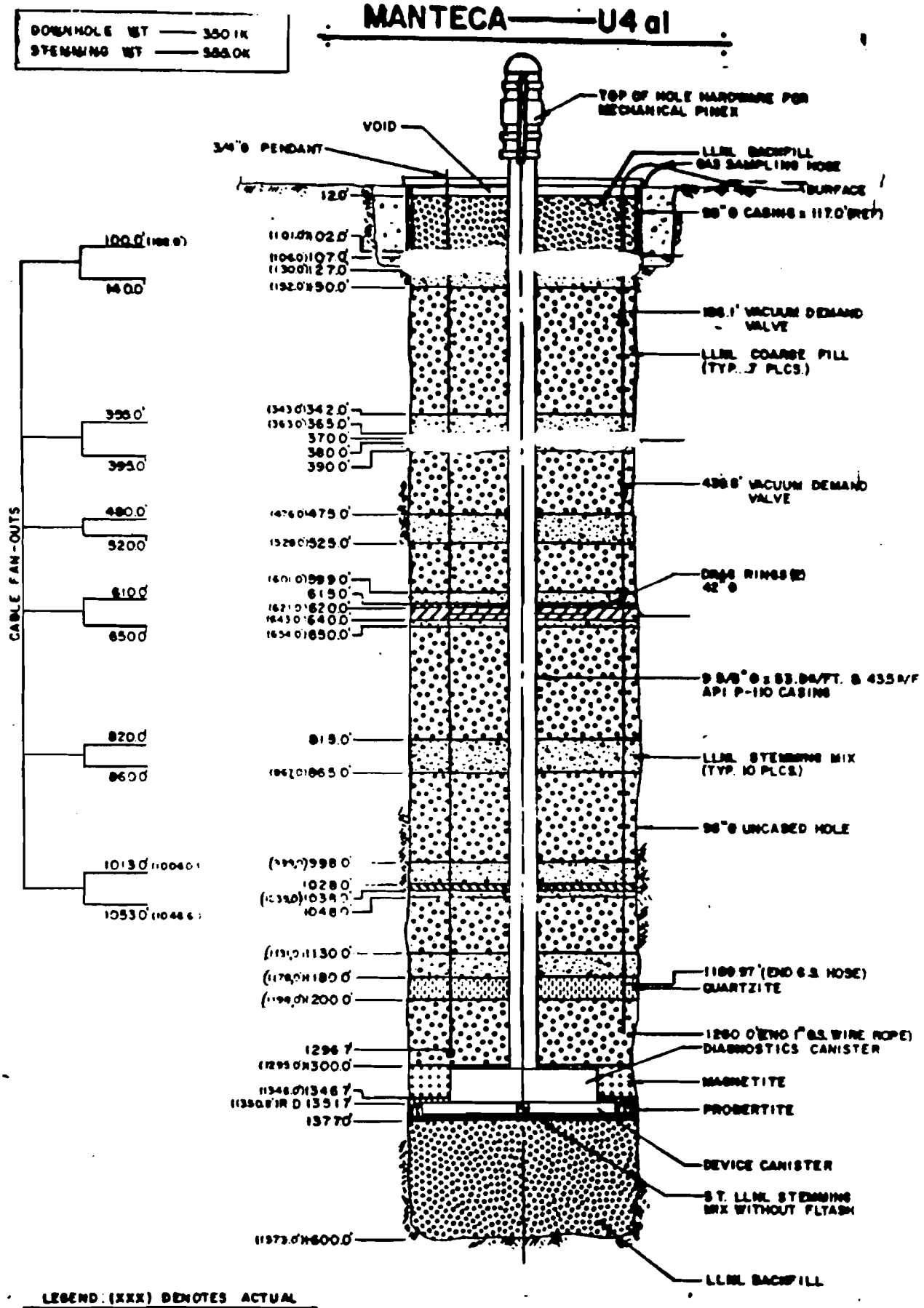

DOWNHOLE WT. — 567 K
STEMMING WT. — 772 K
CABOC — U2cp
PIPE PLUG
GAS SAMPLING ASSEMBLY
BACKFILL
SURFACE
96" DIA SURFACE CASING (REF.)
LAE 69 MT PLASTIC PLUG (TYP 4 PLC'S.)
LAE 99 PLASTIC PLUG
L L N L STEMMING MIX WITHOUT FLYASH
LAE 99 S PLASTIC PLUG (TYP. 4 PLC'S.)
L L N L STEMMING MIX B (TYP 10 PLC'S.)
3/4" (9 X 7 RIPS WIRE ROPE PENDENT
L L N L COARSE FILL (TYP. 7 PLC'S.)
96" DIA UNCASED HOLE
PLUG SUPPORT RINGS (2 - 60" DIA.)
10 3/4" DIA X 710 FT API P-110 CASING
GROUT
QUARTZITE
OVERTON SAND
DIAGNOSTICS CANISTER
DEVICE CANISTER
L L N L STEMMING MIX WITHOUT FLYASH
BACKFILL
LEGEND (XXX) DENOTES ACTUAL

Turning Points in Containment



MANTECA was the first event to include Two Part Epoxy (TPE) plugs

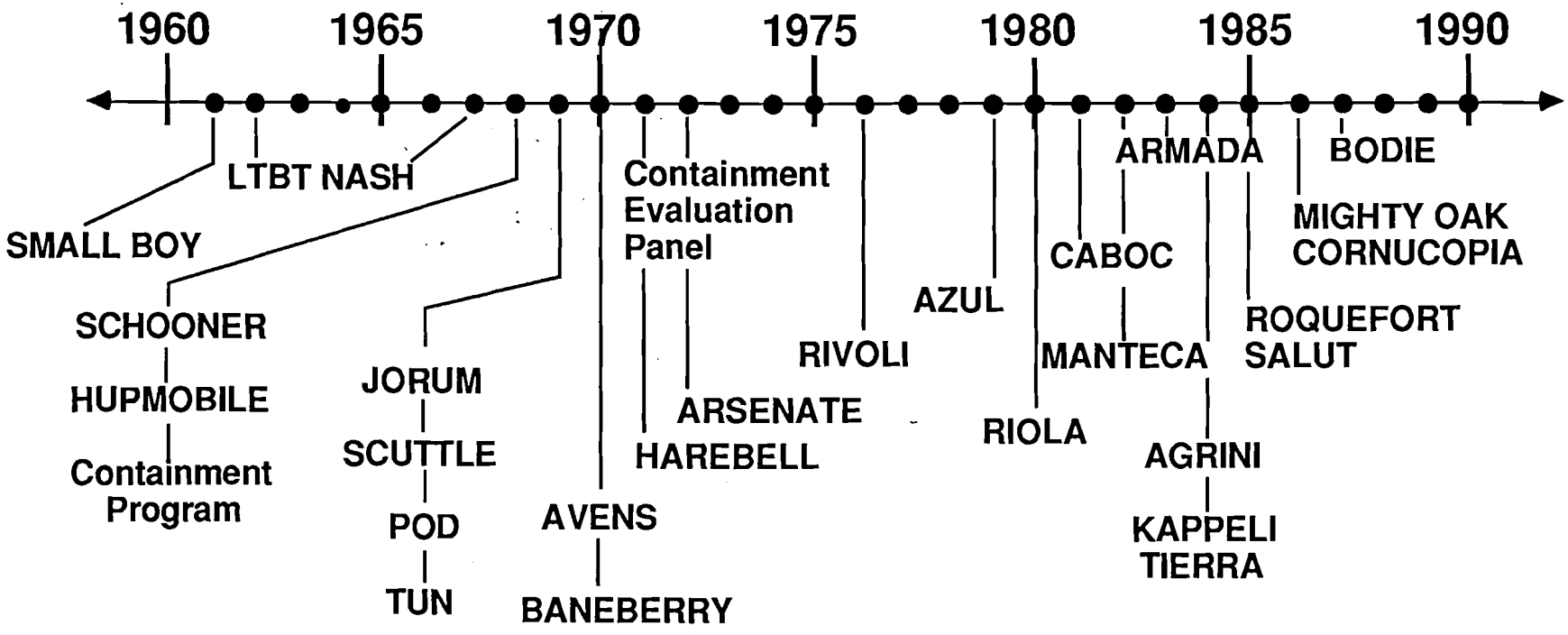
- Field tests showed these plugs to be of high strength
- Field tests also showed they were not as good gas blocks
- All LLNL events from MANTECA (1982) till AGRINI (1984) had TPE plugs



LEGEND: (XXX) DENOTES ACTUAL

HOLMES & NARVER INC

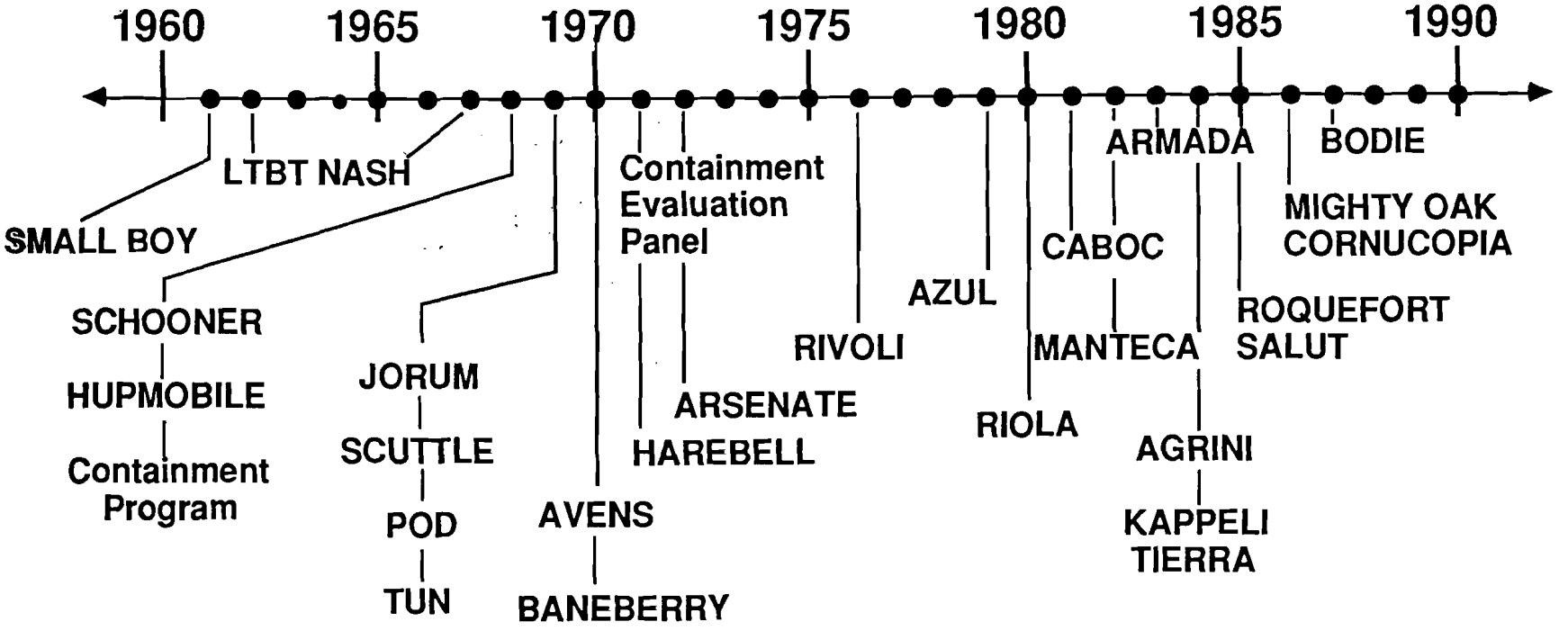
Turning Points in Containment



ARMADA: A fines layer with cable fan-out and gasblocks was not a block to gas flow

- Gas at low pressure passed a 12 m fines layer in a few seconds
- Subsequent fan-outs were improved with wider cable spacings

Turning Points in Containment



AGRINI was the first event since BANEBERRY to have a post-collapse release

- Release was believed to be due to a combination of noncondensible gas and a very deep crater
- Testing was allowed to continue without a significant delay

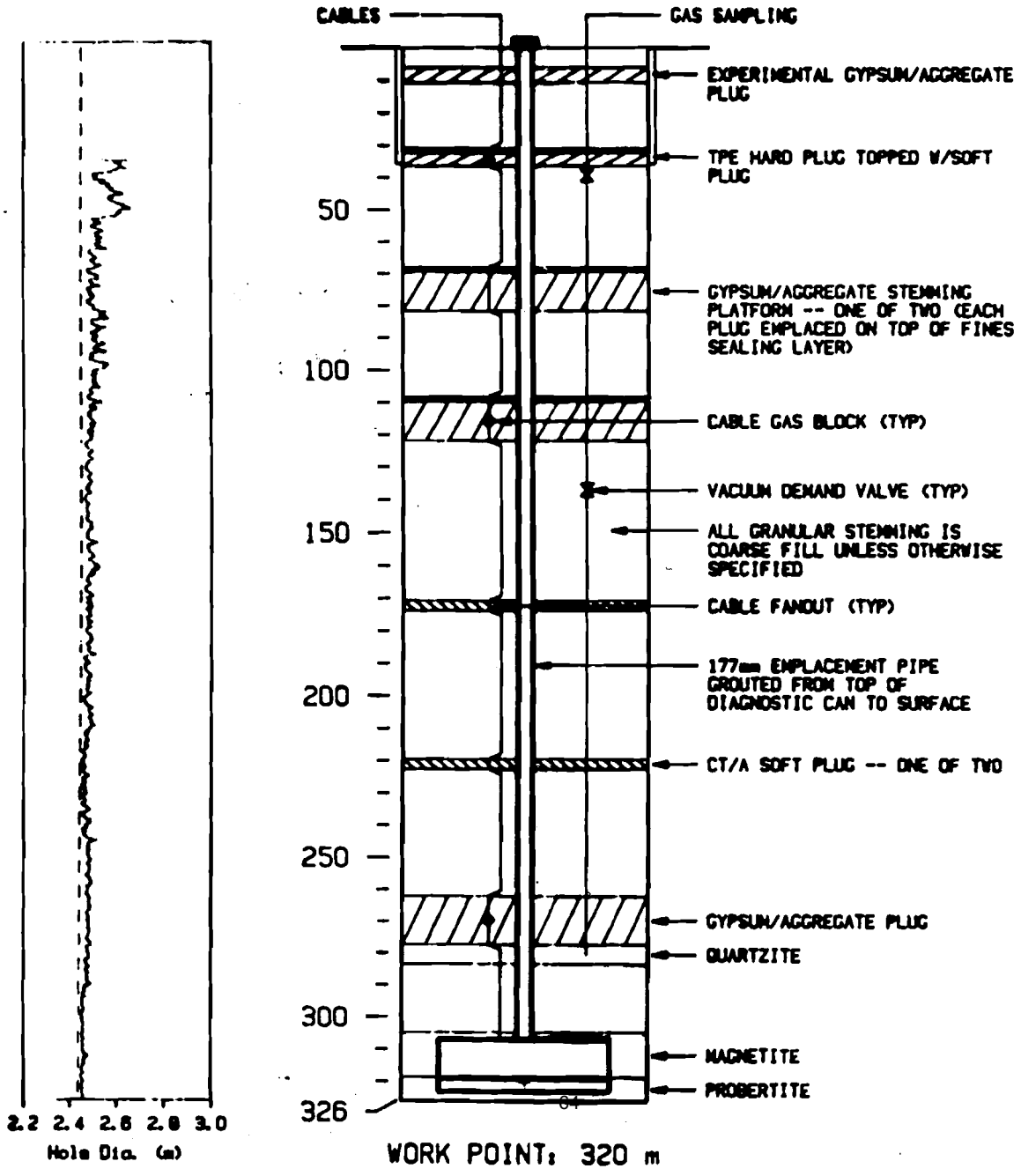
AGRINI was a low yield event detonated on March 31, 1984 at a depth of 320 m in area 2 alluvium

- DOB and SDOB were conservative by historical standards
- Nearby experience was good
- Stemming was carefully designed
- Geologic structure appeared favorable
- Medium properties appeared satisfactory
- Confidence in containment was high ....

AGRINI was the first event to use gypsum concrete plugs and liquid CTE gas impedance plugs

- Stemming platforms were of gypsum/coarse aggregate
- Gas impedance plugs were of liquid CT filled coarse
- The deep plug was of gypsum/coarse aggregate
- Diagnostic data indicate all performed as expected

AGRINI
U2ev


CABLES
GAS SAMPLING
EXPERIMENTAL GYPSUM/AGGREGATE PLUG
TPE HARD PLUG TOPPED W/SOFT PLUG
GYPSUM/AGGREGATE STEMMING PLATFORM -- ONE OF TWO (EACH PLUG EMPLACED ON TOP OF FINES SEALING LAYER)
CABLE GAS BLOCK (TYP)
VACUUM DEMAND VALVE (TYP)
ALL GRANULAR STEMMING IS COARSE FILL UNLESS OTHERWISE SPECIFIED
CABLE FANOUT (TYP)
177mm EMPLACEMENT PIPE GROUTED FROM TOP OF DIAGNOSTIC CAN TO SURFACE
CT/A SOFT PLUG -- ONE OF TWO
GYPSUM/AGGREGATE PLUG
QUARTZITE
MAGNETITE
PROBERTITE
50
100
150
200
250
300
326
2.2 2.4 2.6 2.8 3.0
Hole Dia. (m)
WORK POINT: 320 m

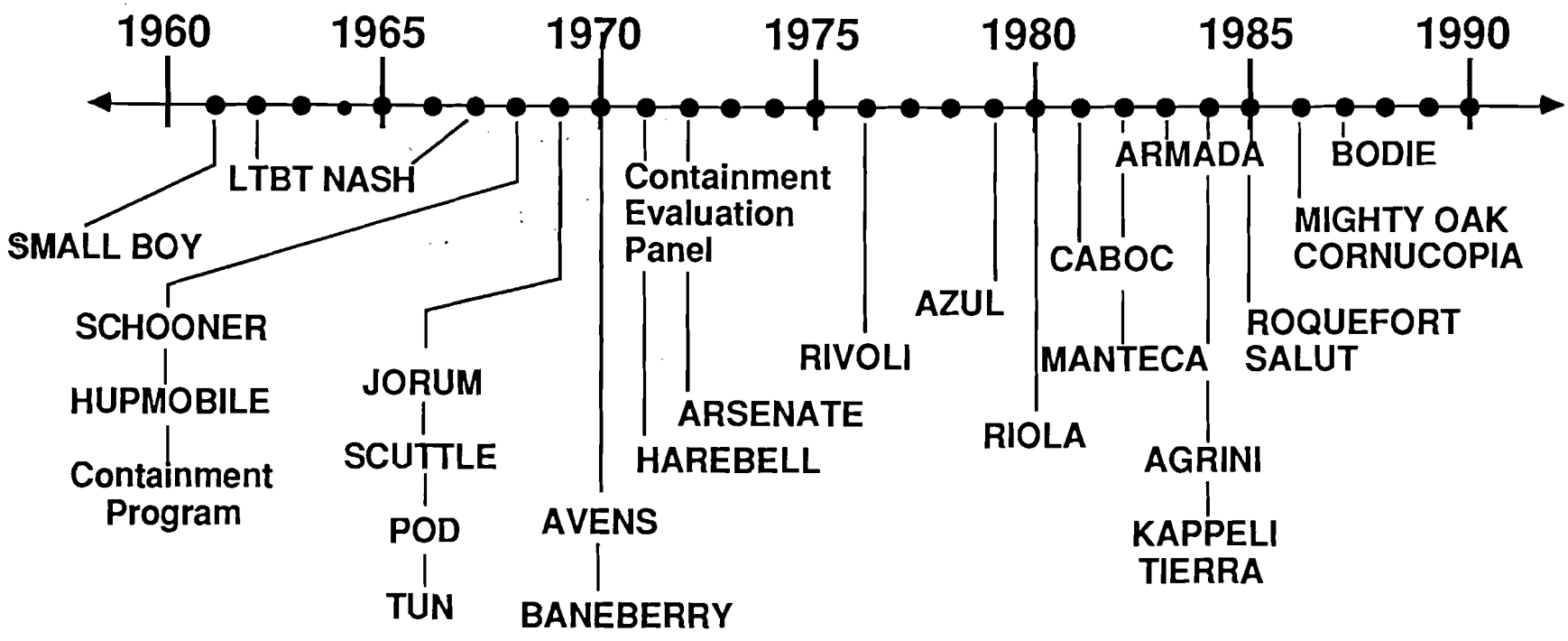
AGRINI behavior was not anticipated

- A very deep (67 m), narrow (12 m diameter at the surface), bottle-shaped crater was formed at about 1 3/4 hours after detonation
- About eight hours later, unexpected radioactivity was detected on the surface
- During the following 26 hours, about 1700 Ci (predominately isotopes of Xe) were determined to have been released
- All activity appeared to come from the crater

Conclusions

- The emplacement hole was not part of the release path
- The deep bottle-shaped crater was due to strong near-surface material
- The near-surface driving pressure in the chimney was largely due to CO_2
- A minor reduction of CO_2 could have changed the transport mechanism from pressurized flow to diffusion coupled with atmospheric pumping, greatly delaying and reducing the release
- A major reduction in CO_2 would have essentially prevented the release

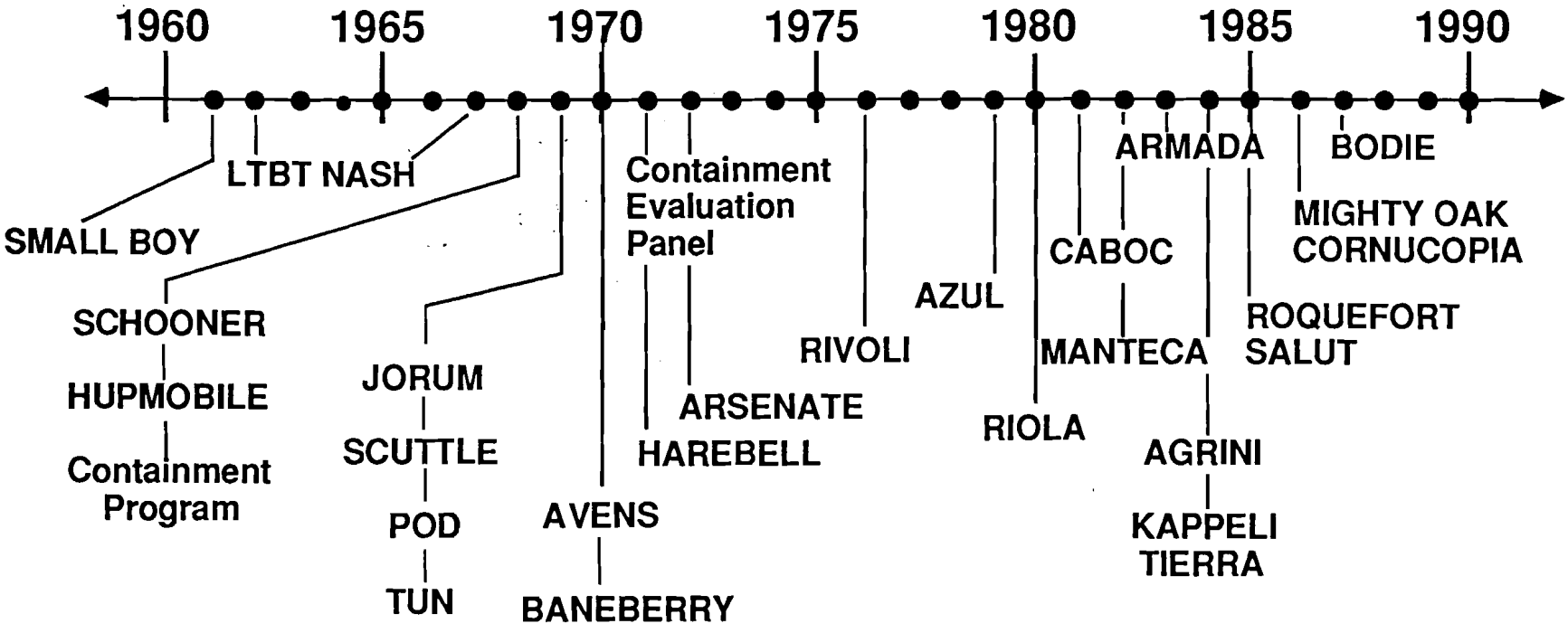
Turning Points in Containment



KAPPELI and TIERRA were Pahute Mesa events where very low level radioactivity could be monitored for long periods of time

- Both events were observed to "leak" days after detonation
- A recent study by Erv Woodward suggests late-time leakage on the MESA is related to near surface geology

Turning Points in Containment

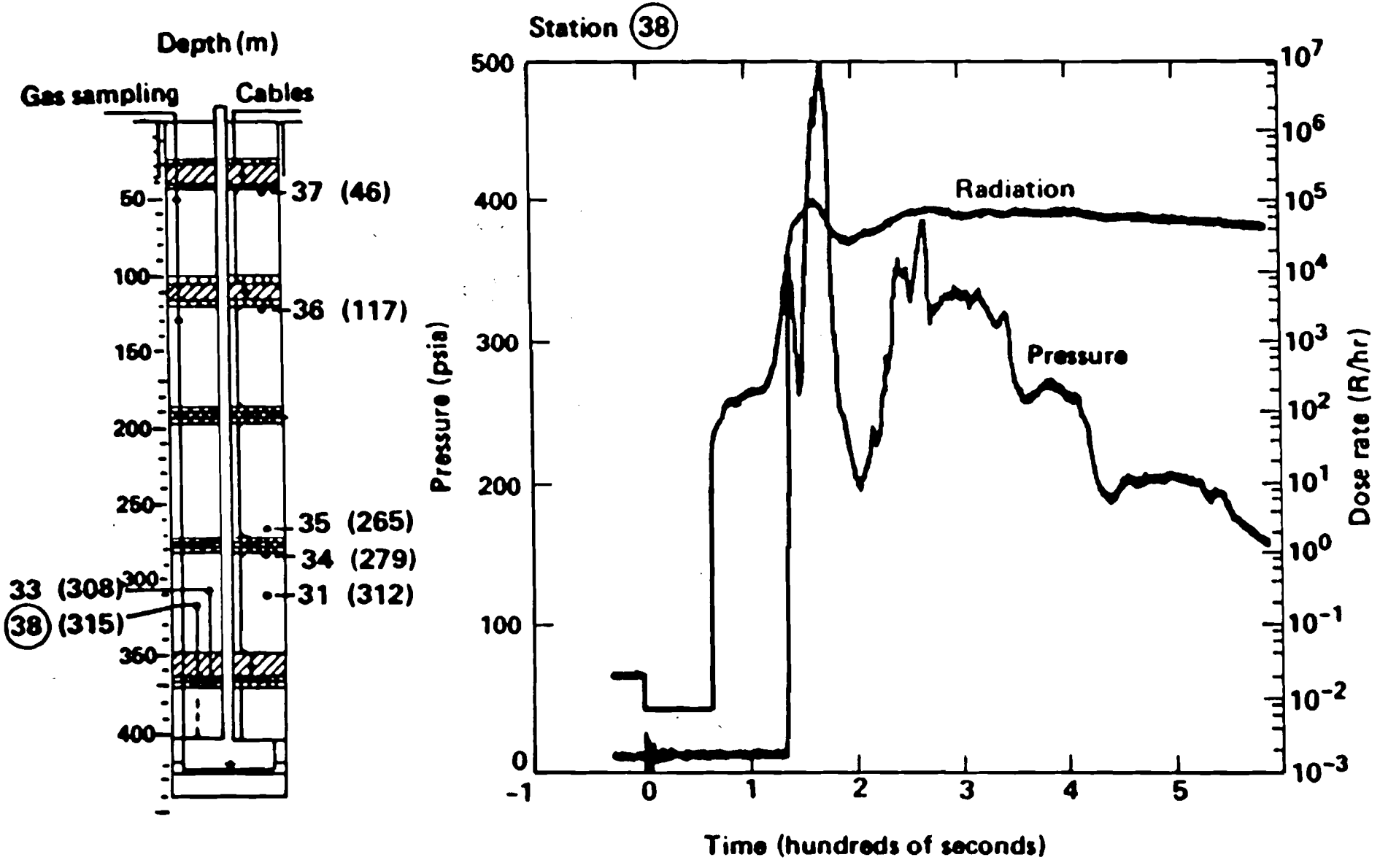


ROQUEFORT data indicate that

- Gypsum/aggregate plugs are not reliable as gas blocks
- Liquid coal-tar/aggregate plugs cannot be reliably made to stay in place
- ROQUEFORT had the highest pressure levels observed in the stemming column since BANBERRY
- Subsequent events have had "sanded" gypsum plugs, mixed at the surface and pumped to depth

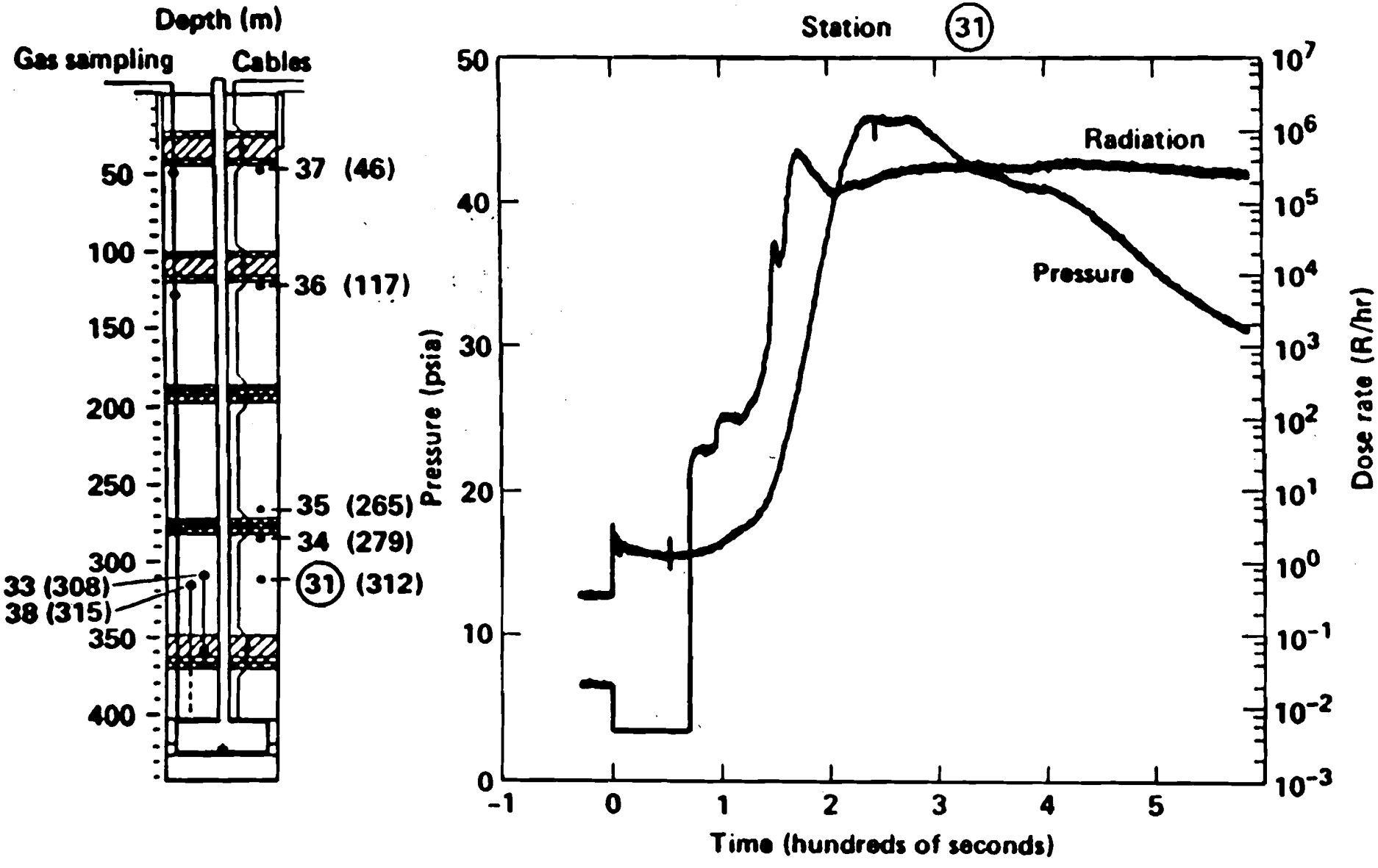
ROQUEFORT

The deep gypsum plug offered very little impedance to the early flow of gas.

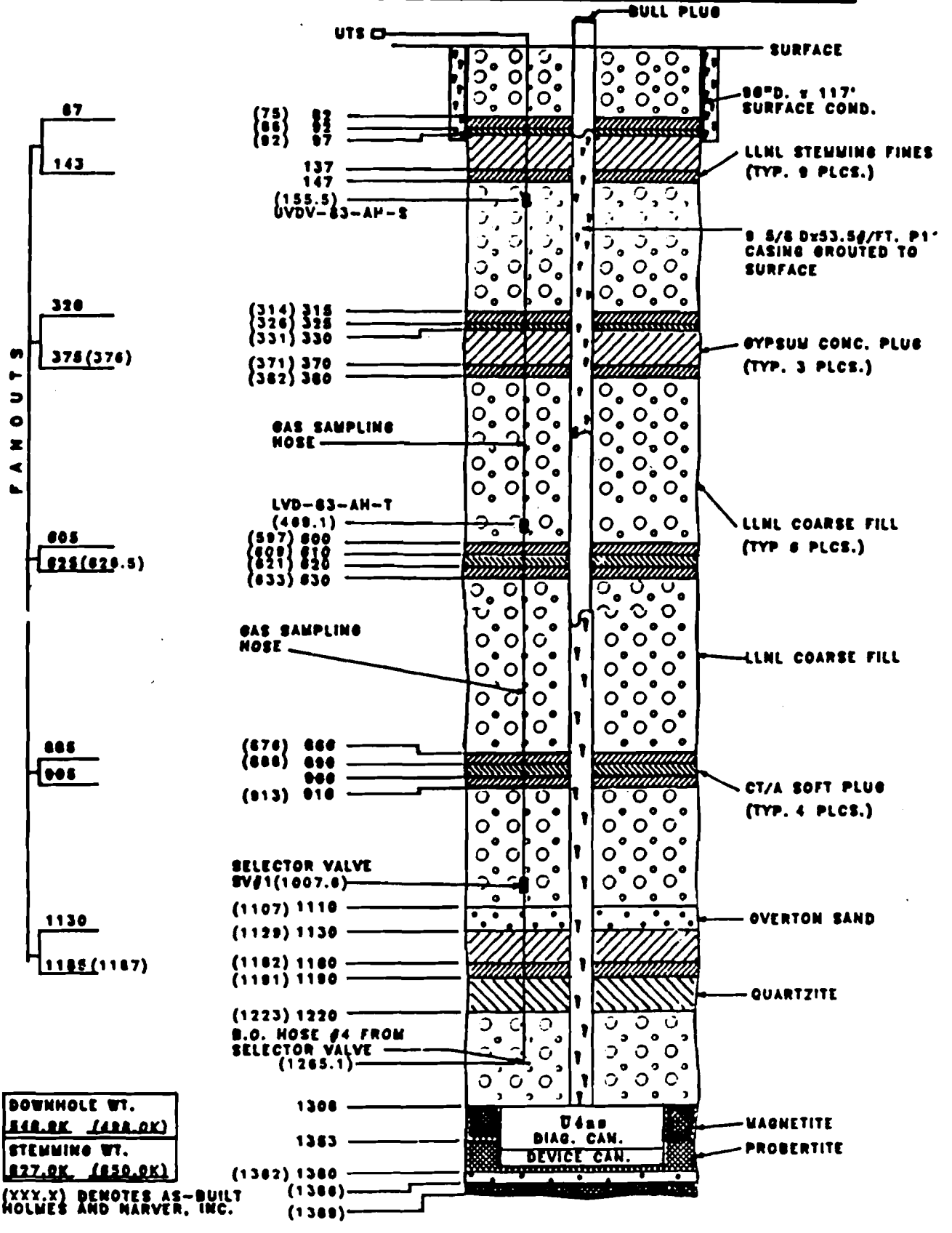


ROQUEFORT

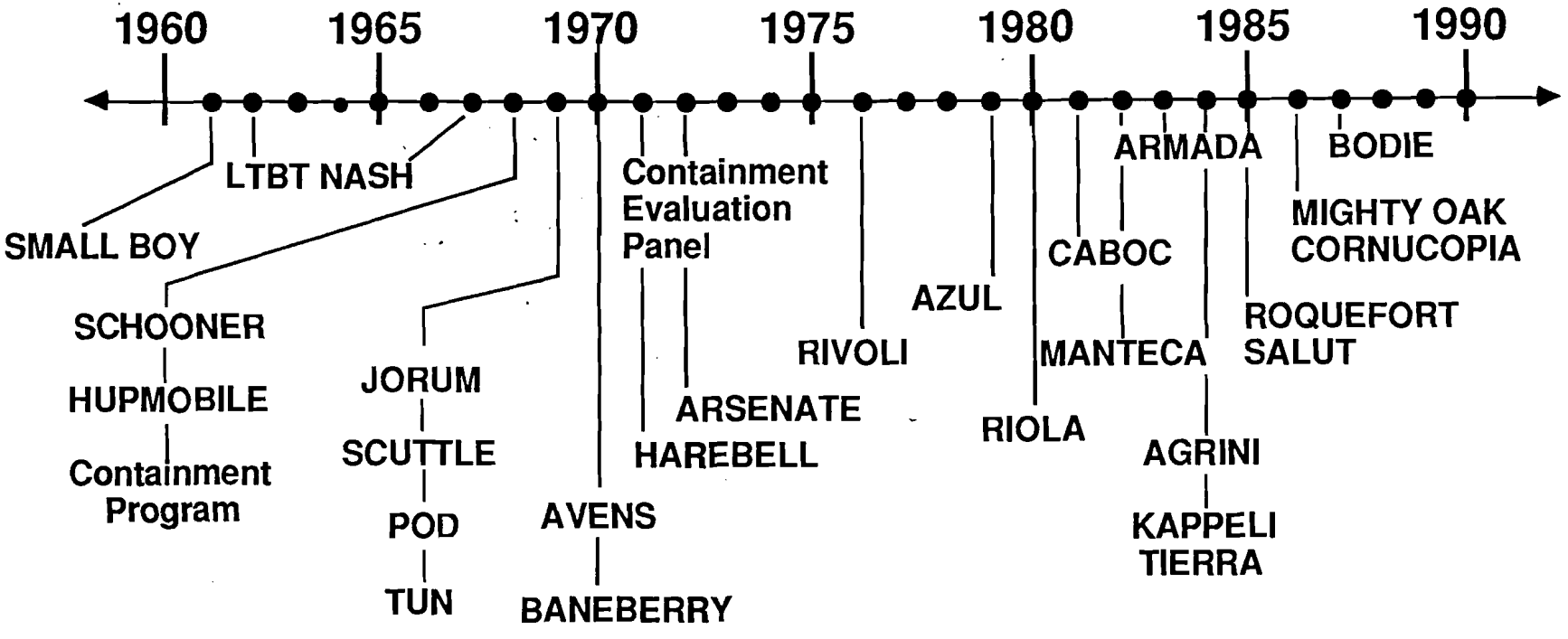
The deep gypsum plug offered very little impedance to the early flow of gas.



ROQUEFORT — U4as



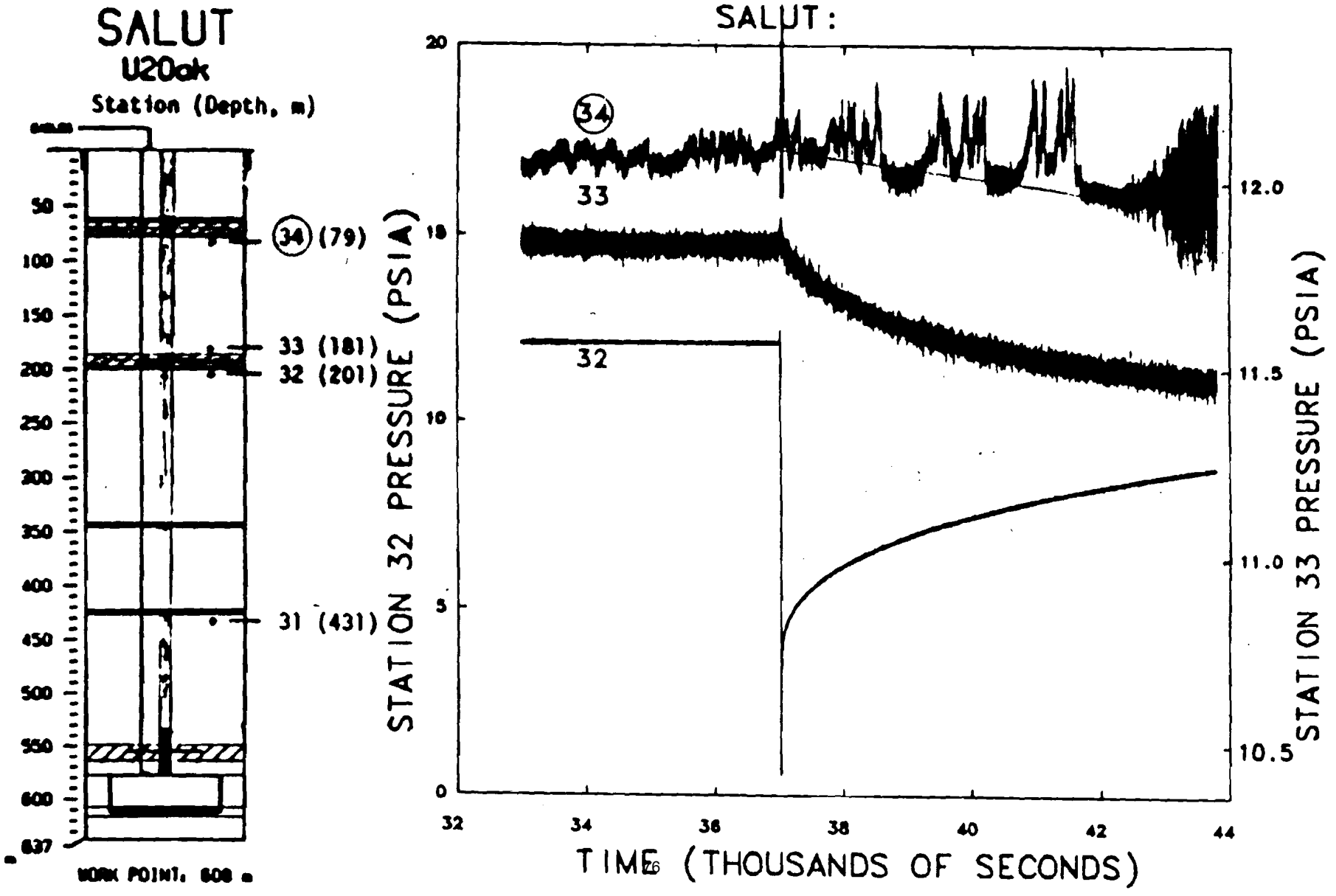
Turning Points in Containment



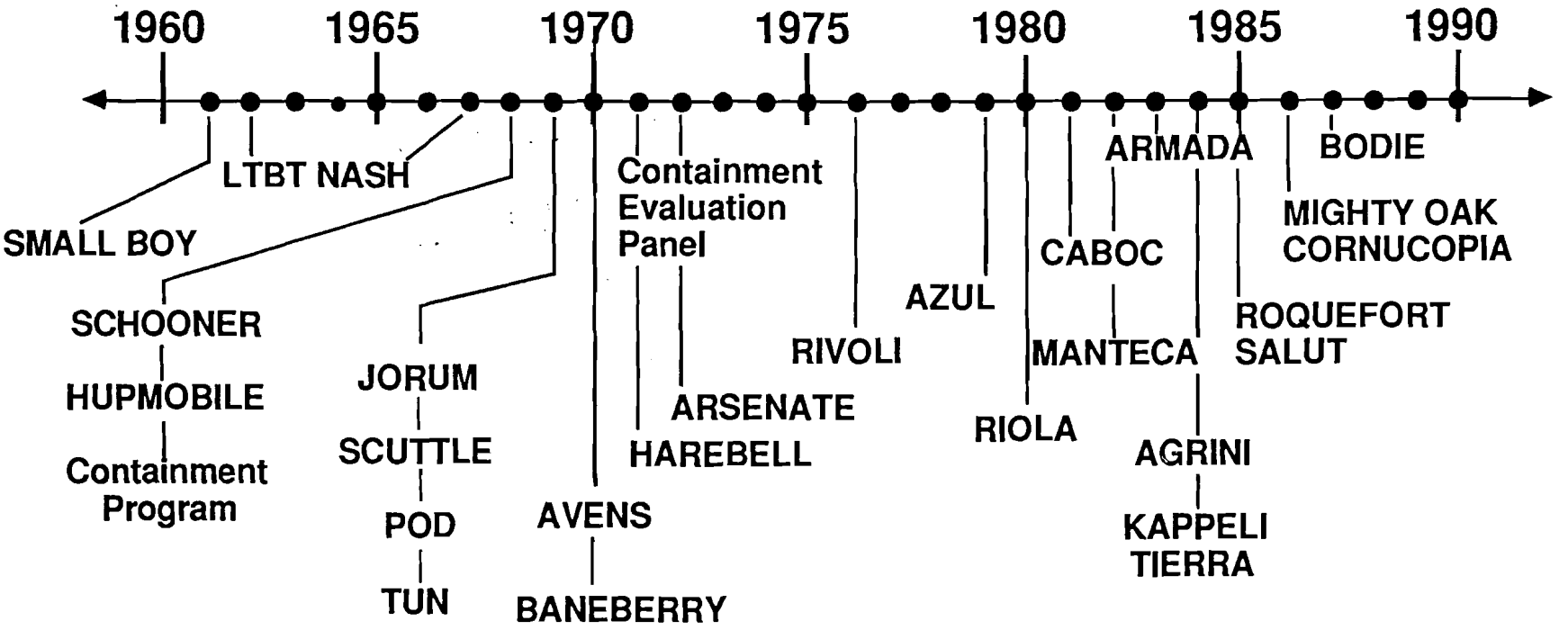
PERFORMANCE: SALUT

- THE STEMMING PLATFORM PERFORMED AS STRUCTURAL MEMBER

- THE STEMMING PLATFORM MAY HAVE BEEN PERMEABLE TO LOW PRESSURE AIR FLOW

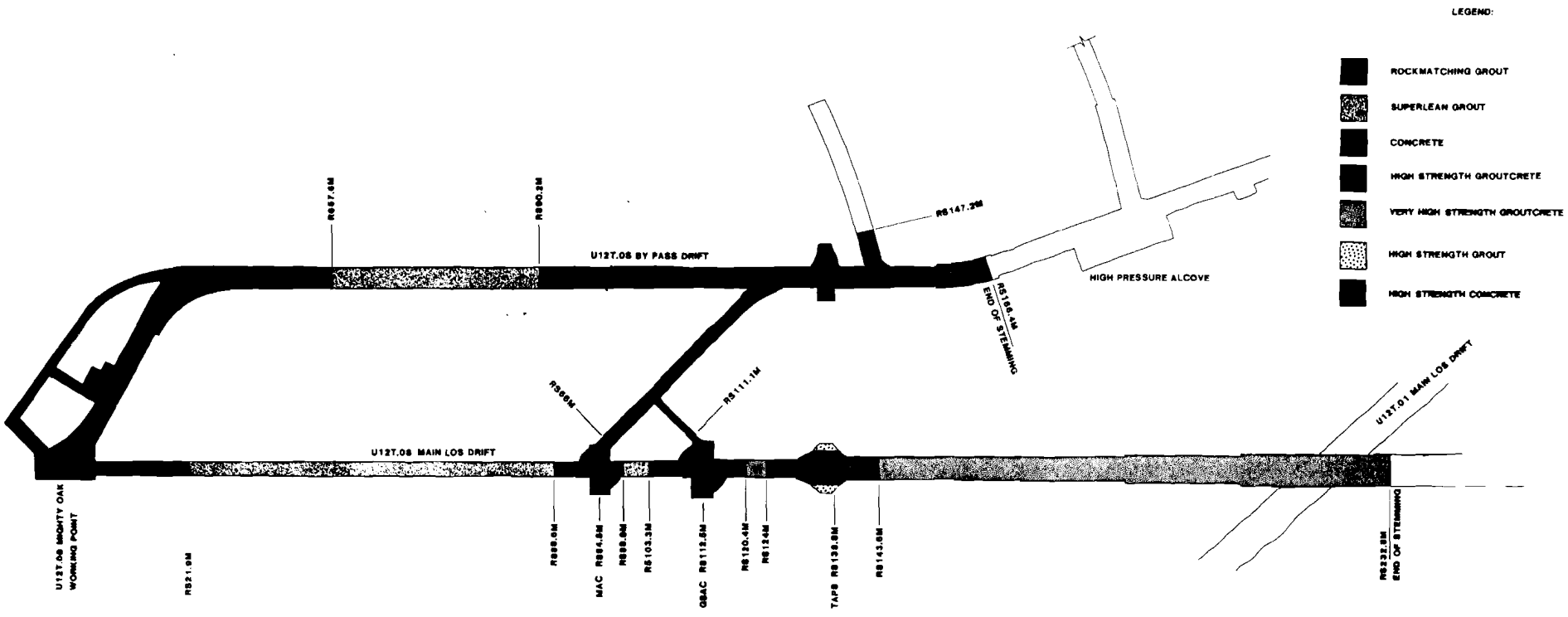

SALUT
U20ak
Station (Depth, m)
50
100
150
200
250
300
350
400
450
500
550
600
637
34 (79)
33 (181)
32 (201)
31 (431)
WORK POINT, 608 m
SALUT:
34
33
32
STATION 32 PRESSURE (PSIA)
STATION 33 PRESSURE (PSIA)
TIME (THOUSANDS OF SECONDS)
20
15
10
5
0
12.0
11.5
11.0
10.5
32
34
36
38
40
42
44

Turning Points in Containment



MIGHTY OAK had an experiment protection problem

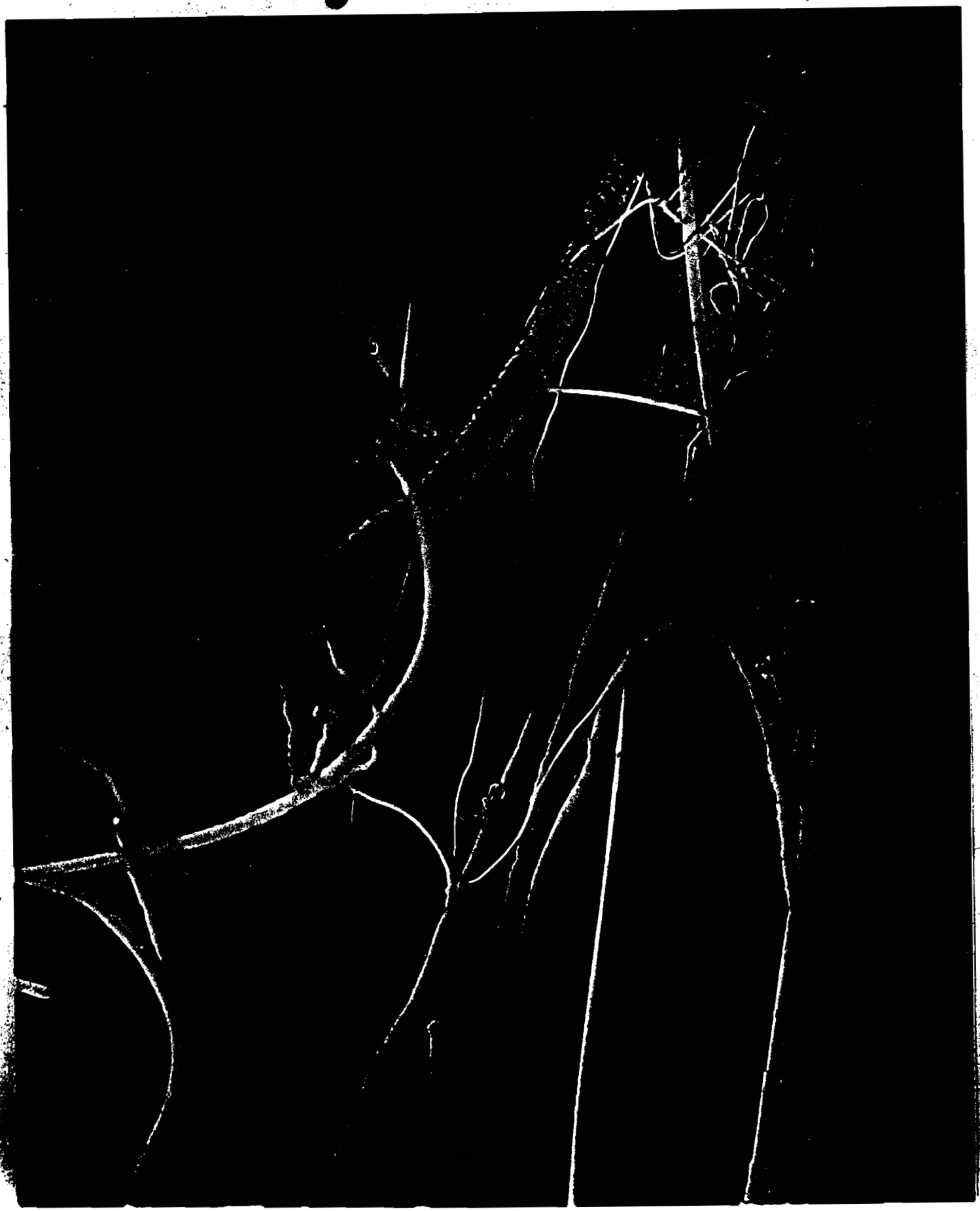
- Containment was satisfactory
- LOS closure was unsuccessful
- Exposure chamber experiments were lost
- Most tunnel recording facilities were lost

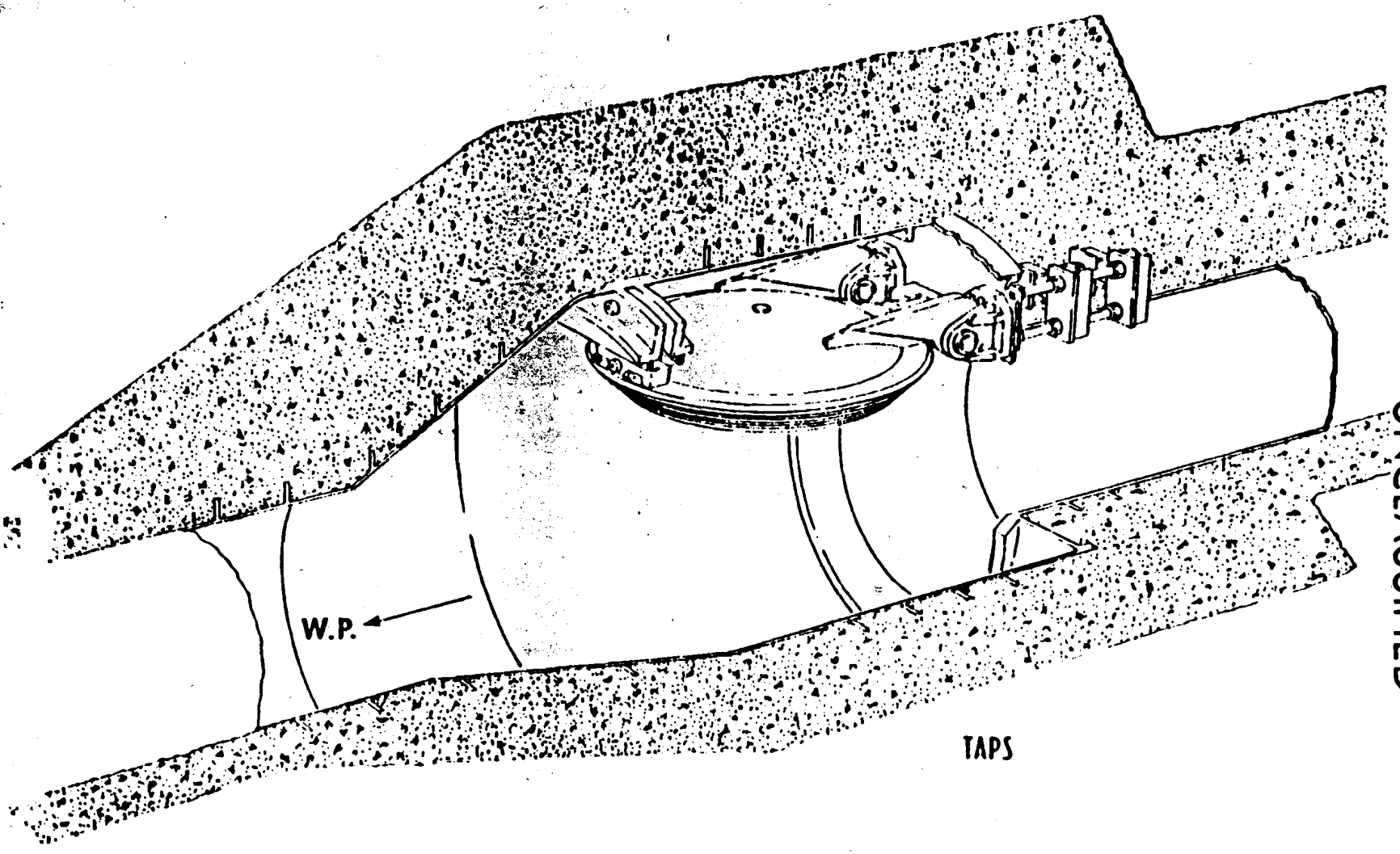


MIGHTY OAK STEMMING PLAN

PAN AM — DNA PHOTO
NEG. NO. CQ151-2

Recording Alcove





UNCLASSIFIED

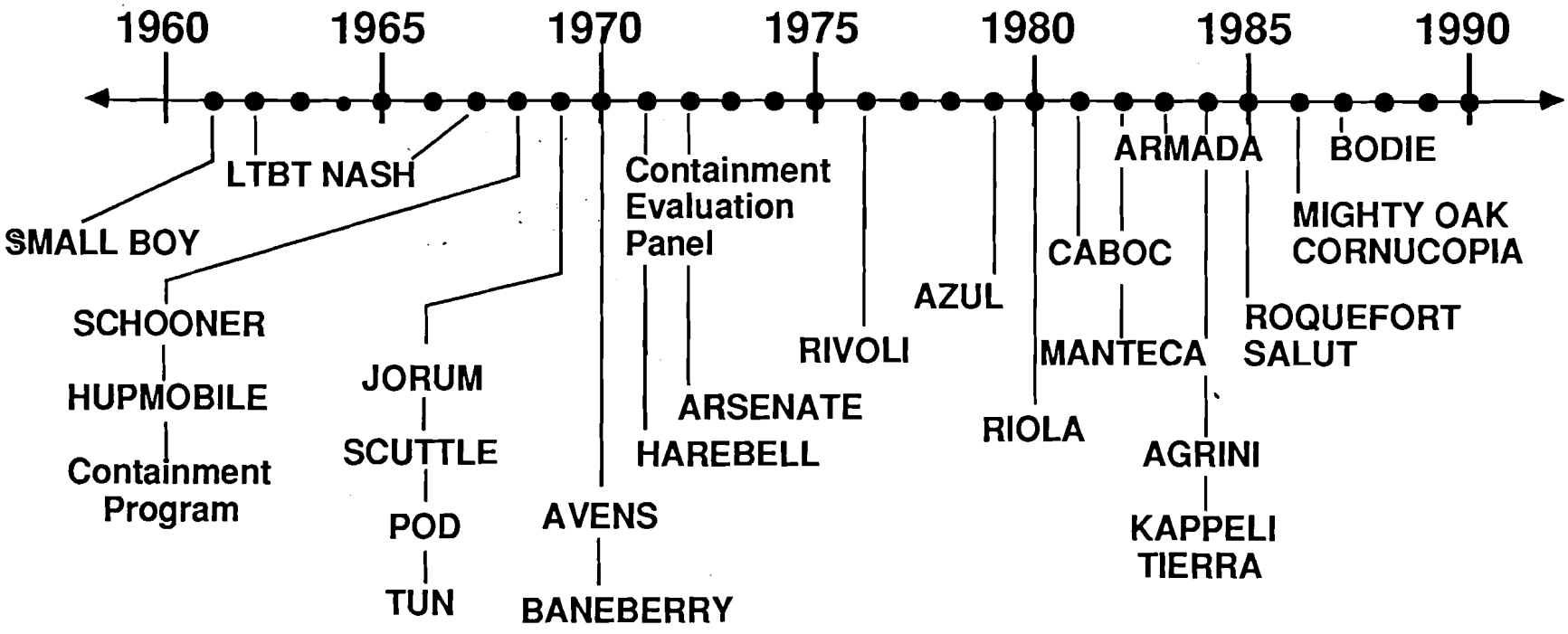
1000 psi, 1000 °F

Figure D-5. Tunnel and Pipe Seal Taps

The MIGHTY OAK investigation is incomplete; however, MIGHTY OAK findings are consistent with several possible threats

- Unfavorable near-cavity geology
- Failure of the LOS pipe system
- Failure of the tunnel stemming
- Combinations of the above

Turning Points in Containment

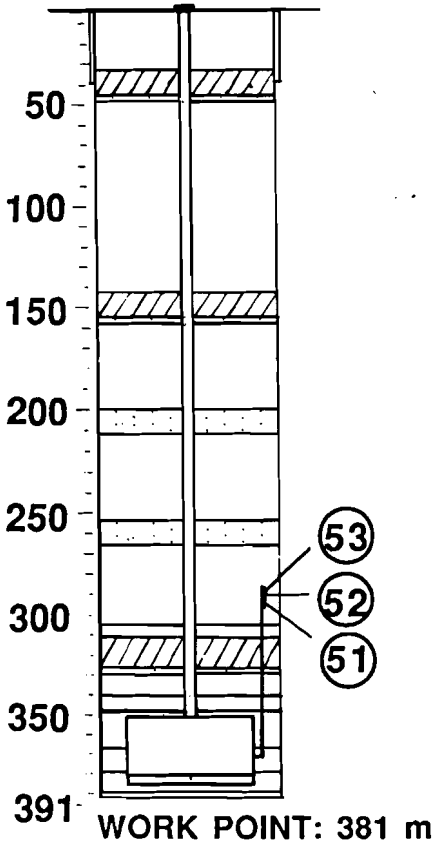


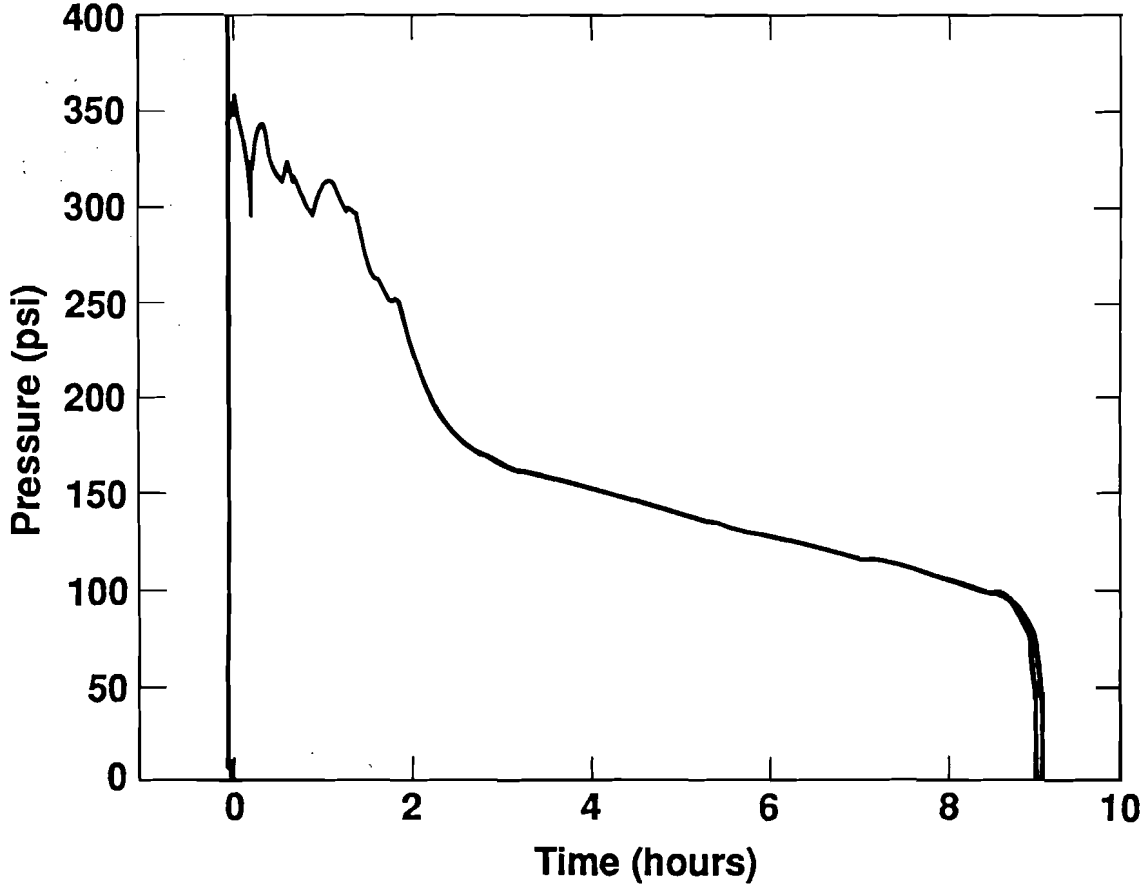
The first successful measurements of a complete cavity pressure history were made on CORNUCOPIA

- Three independent measurement systems gave almost identical pressure histories extending from about 30 s until collapse at about 9 hr
- Similar data were obtained from two other events

CORNUCOPIA

Cavity pressure was measured until collapse at about nine hours





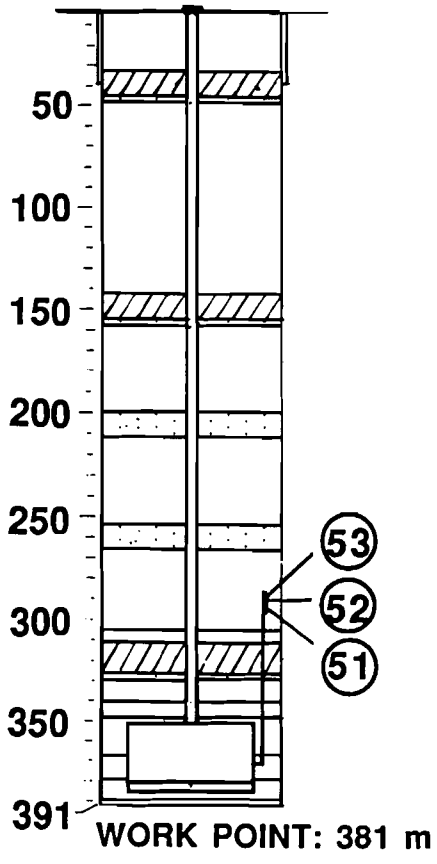
CORNUCOPIA

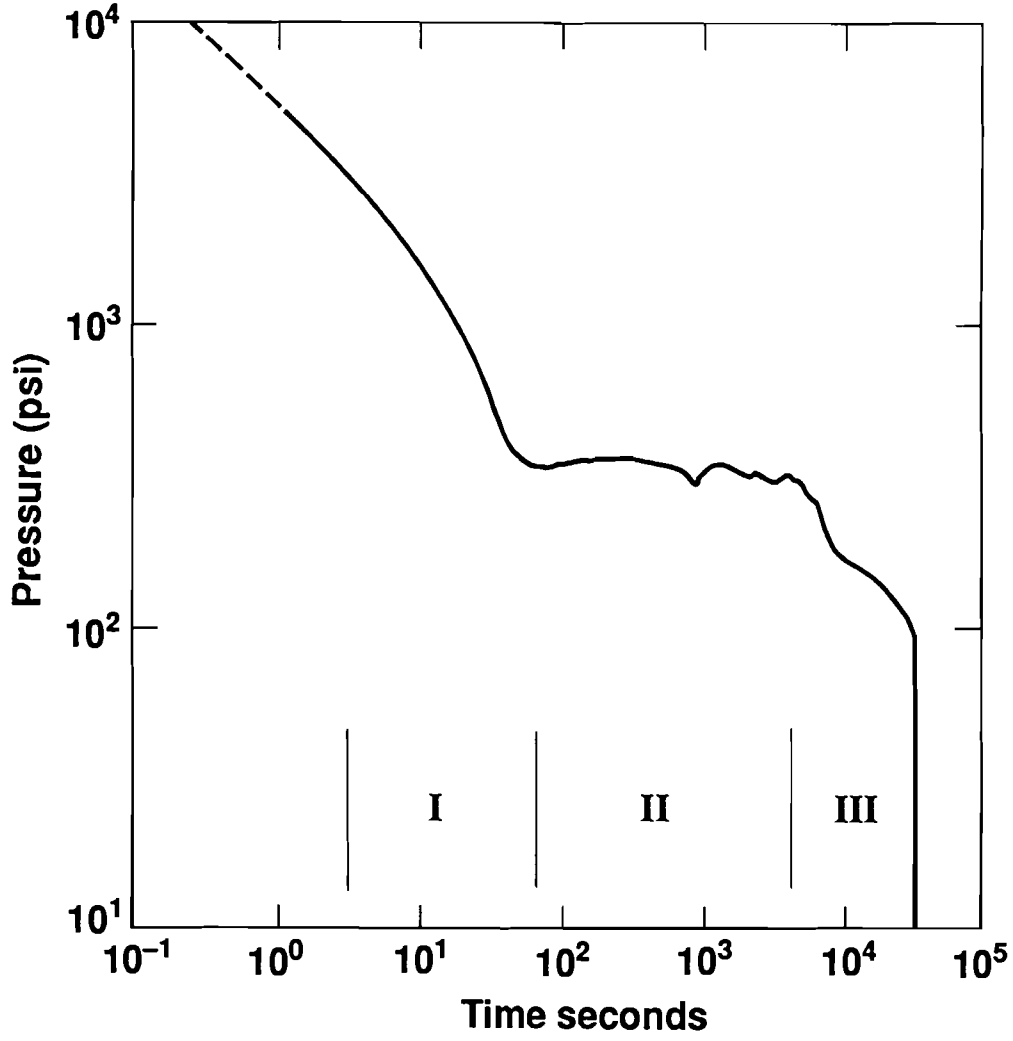
Calculational analysis suggests a model:

- Hydro fracture allows the pressure to drop to about 30 bars within 100 seconds (Stage I)
- Wall ablation brings mass into the cavity for about one hour (Stage II) causing the temperature to drop to near the melting point of rock (~1400K) with little change in pressure
- Heat conduction into the cavity wall cools the remaining gas with a commensurate pressure decay until collapse (Phase III)

CORNUCOPIA

A log-log plot of pressure suggests three stages of decay



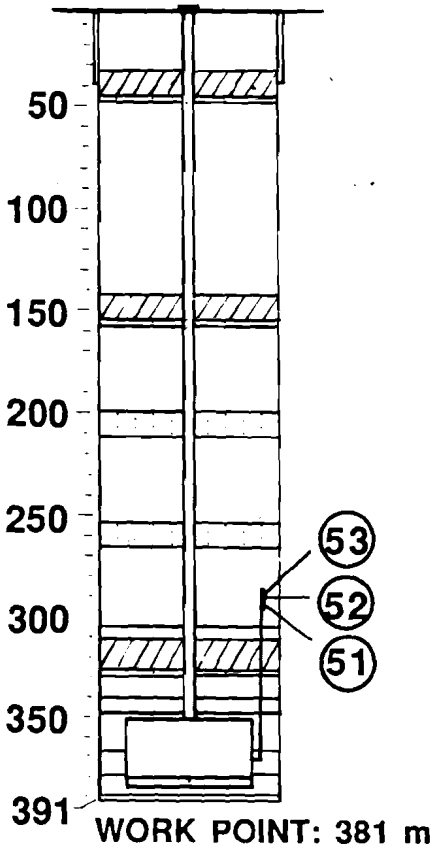


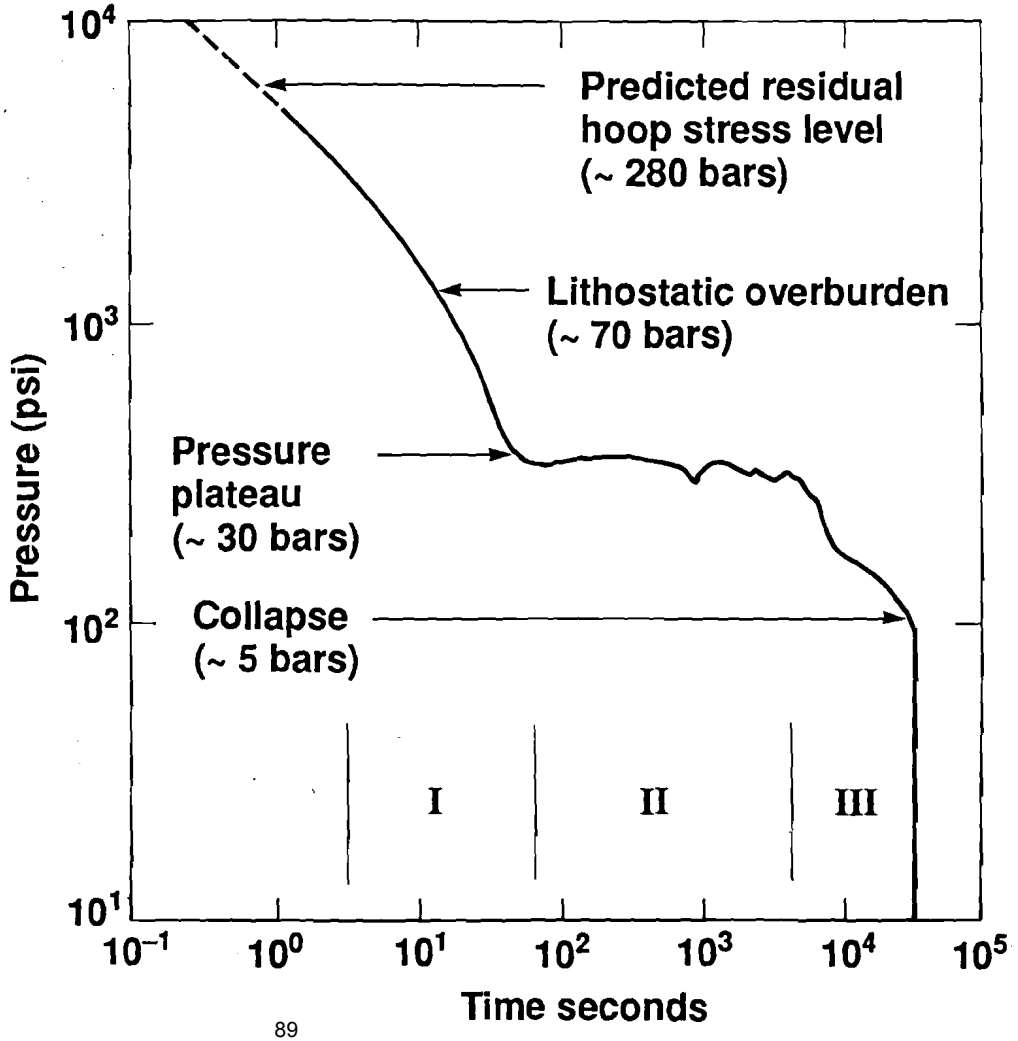
CORNUCOPIA

If this model has credibility-----

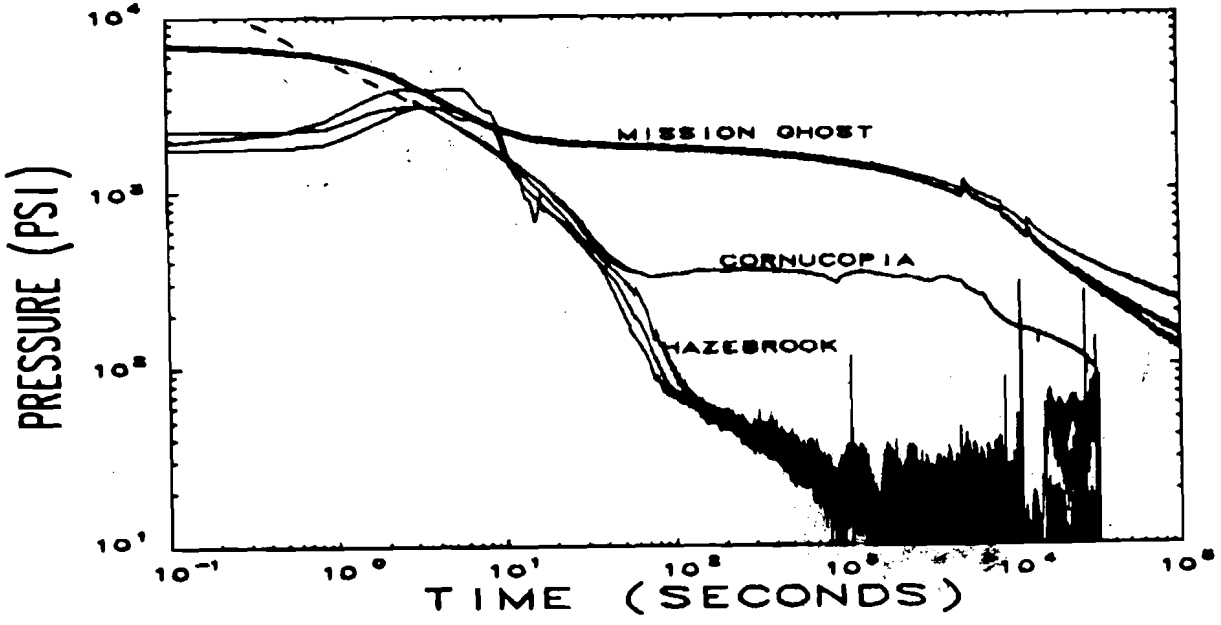
- Why wasn't residual hoop stress effective in controlling hydrofracture?
- Would hydrofracture limitation have been beneficial ?
- Should the potential for the storage of hydrofracture effluent be an important consideration on future events?
- Should hydrofracture crack length be an important siting criterion?

CORNUCOPIA


50
100
150
200
250
300
350
391
53
52
51
WORK POINT: 381 m


Predicted residual hoop stress level (~ 280 bars)
Lithostatic overburden (~ 70 bars)
Pressure plateau (~ 30 bars)
Collapse (~ 5 bars)
Pressure (psi)
10^4
10^3
10^2
10^1
I
II
III
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
Time seconds

Similar data were obtained from two other events



The major containment problem areas were recognized as:

- Near cavity geology
- Overburden geology
- Stemming
- Cables and cable bundle
- LOS pipes

It was generally believed (I should say hoped) that relevant problems could be solved within two years and we could get on with more interesting work

Perceived solutions

Near-cavity geology:

- Avoid high CO_2 content
- Avoid extremely strong or weak materials
- Choose "nominal" medium properties

Perceived solutions (continued)

Overburden geology:

- **Avoid major faults and pre-existing fractures**
- **Avoid media likely to fracture to the surface**
- **Choose a conservative DOB, SDOB**
- **Use a surface casing as deep as practicable**

Perceived solutions (continued)

Stemming and cables:

- **Use low permeability stemming**
- **Use stemming platforms**
- **Use downhole cable gas blocks**

Perceived solutions (continued)

Line-of-sight (LOS) pipes:

- Use device-driven "prompt" closures
- Use "mufflers" for choking flow
- Use high-explosive-driven closures to stop flow
- Use assorted, redundant, mechanical closures to stop leakage

We also adopted a more aggressive diagnostics philosophy

- A feature worth emplacing is worth diagnosing

  Emplacement and quality assessment: was the "as-built" consistent with the "design"?

  Performance: did the feature perform as expected ?

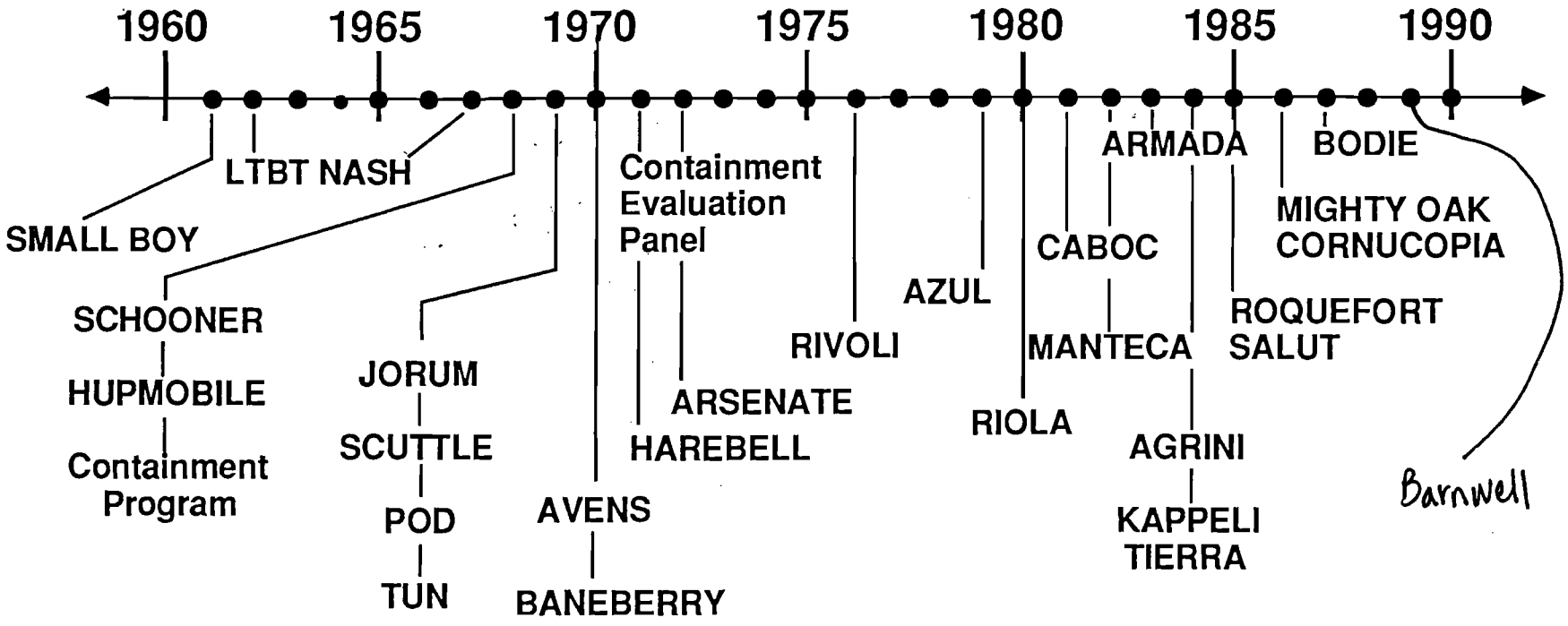
- Phenomenology: was actual behavior consistent with model or calculational predictions ?

Where do we go from here ?

Diagnostics related activities will include:

- Cable bundle block developement
- Plug fracture experiments
- Cavity gas pressure and temperature measurements
- Stress history measurements
- Early gas transport modeling -- hydrofracture
- Late-time gas transport modeling - Darcian flow
- More, better, and faster at lower cost

Turning Points in Containment



We feel that the Barnwell test, conducted in 1989, would have made Hudson's list of turning points in Containment.

Phenomenology: was the actual behavior consistent with model or calculational predictions?

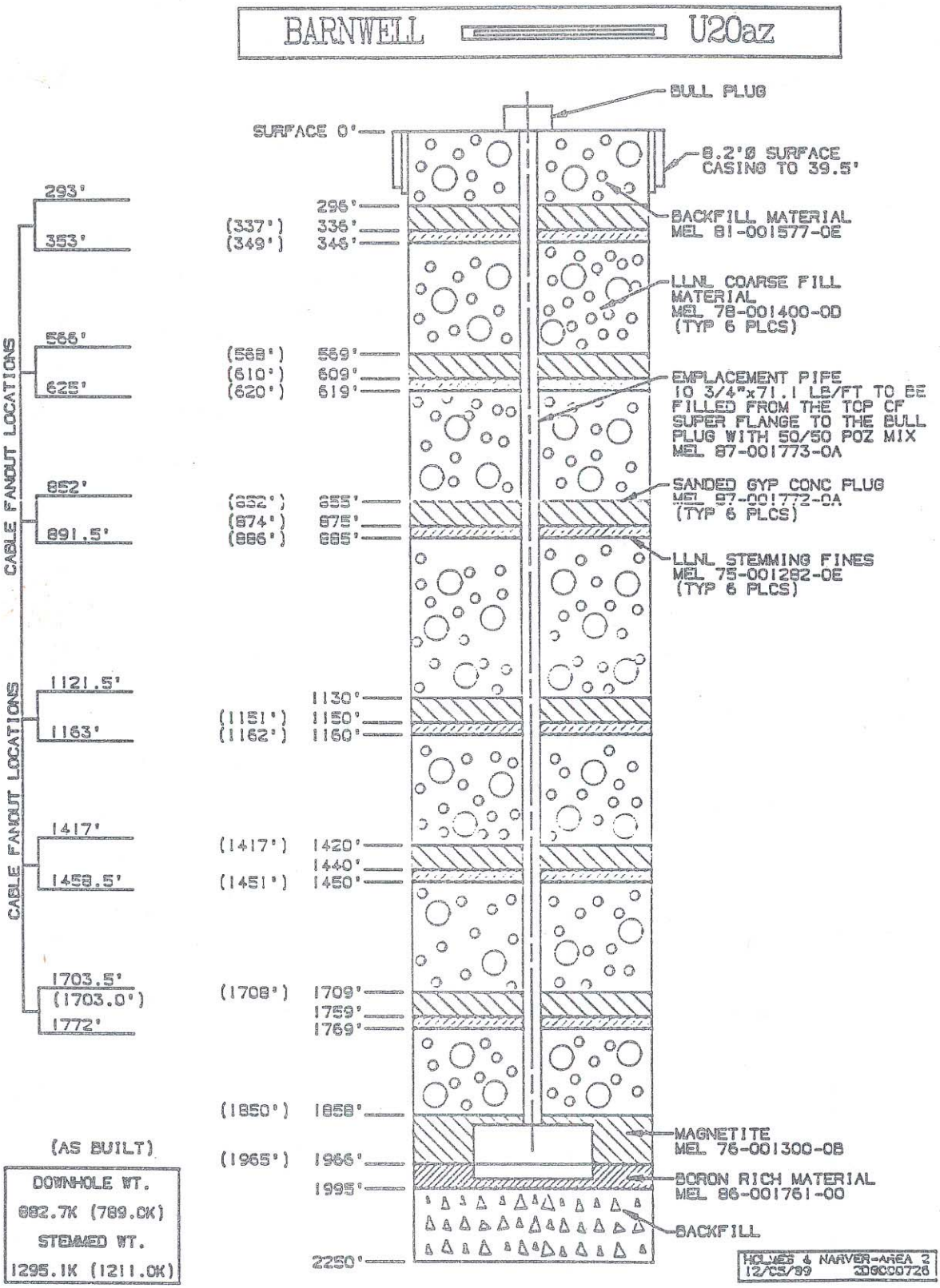
- Pre-test calculations indicated possible residual stress less than cavity pressure
- Because of this a larger than usual set of diagnostics was fielded

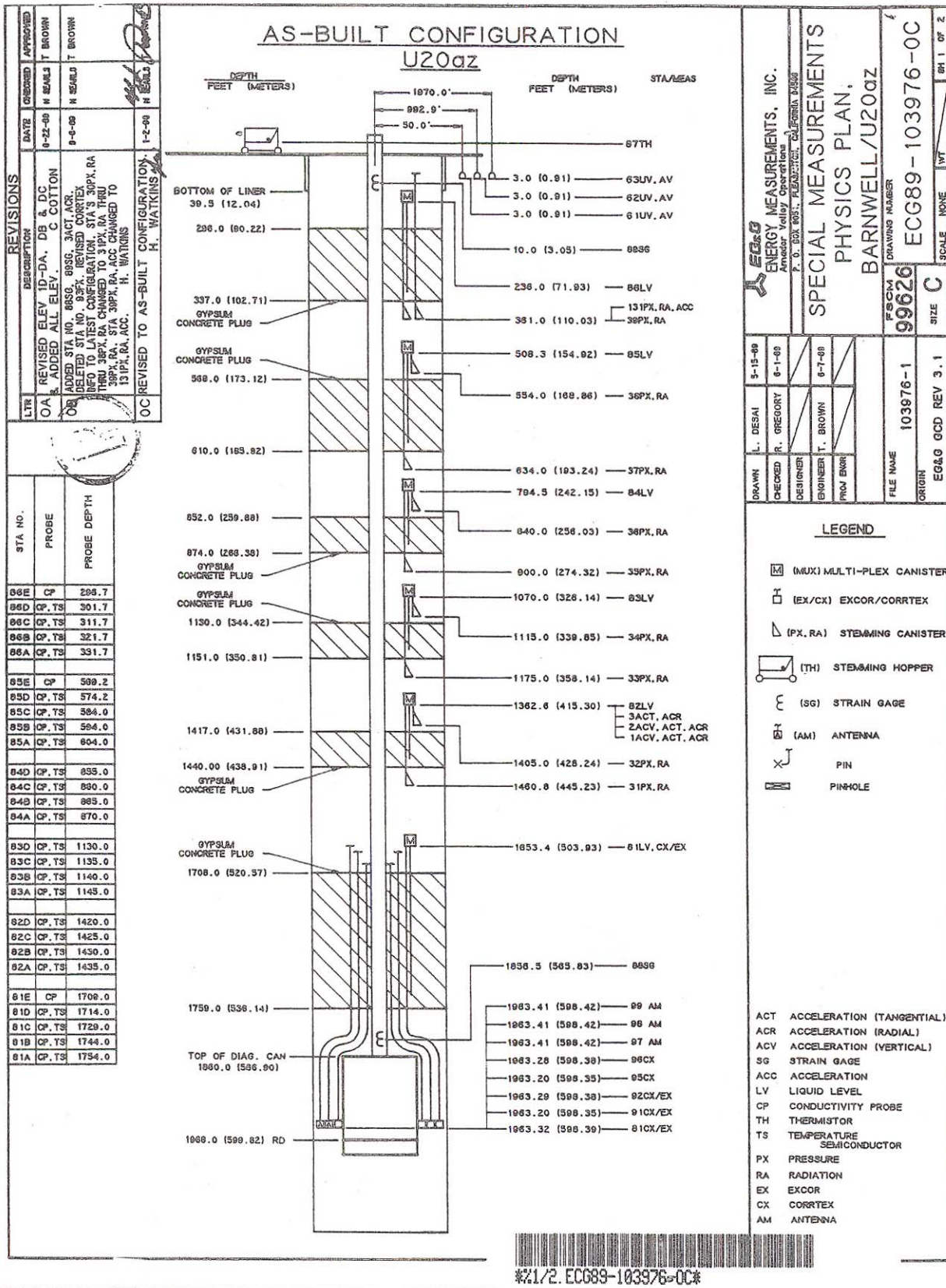
March 2006

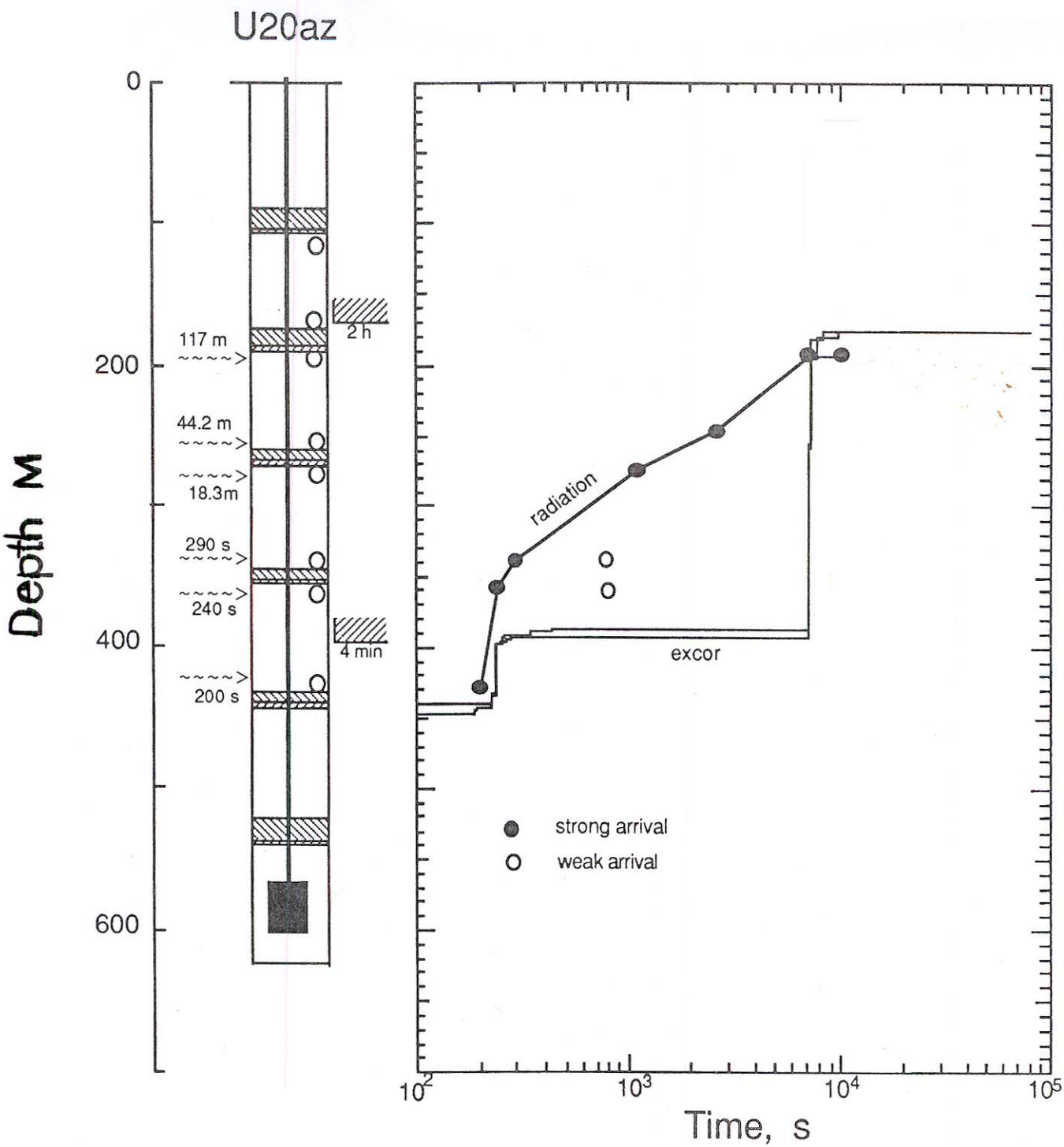
Radiation was detected below the stemming platform for Barnwell.

- Barnwell exhibited a 2-stage collapse (~4 min and ~2 hr)
- 50,000 R/hr was observed ~430 m depth in 4.2 min
- 600 R/hr was observed at ~200 m depth in 3 hr
- Post-test calculations show loss of residual stress above the cavity in the direction of radiation flow
- Radioactivity is rarely encountered uphole for tests >100 kt

March 2006

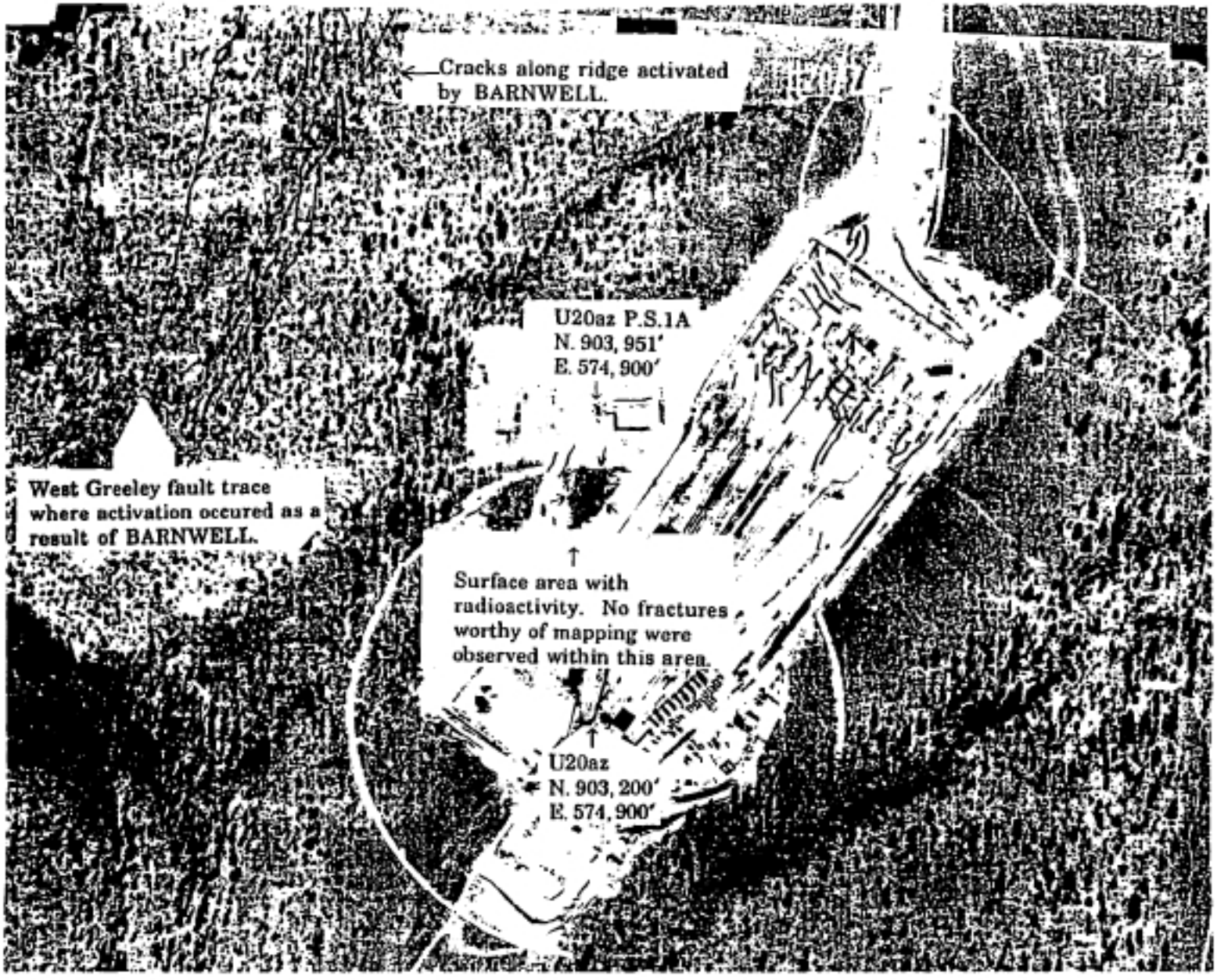

BARNWELL
U20az
BULL PLUG
SURFACE 0'
8.2'Ø SURFACE CASING TO 39.5'
BACKFILL MATERIAL MEL 81-001577-0E
LLNL COARSE FILL MATERIAL MEL 78-001400-0D (TYP 6 PLCS)
EMPLACEMENT PIPE 10 3/4"x71.1 LB/FT TO BE FILLED FROM THE TOP OF SUPER FLANGE TO THE BULL PLUG WITH 50/50 POZ MIX MEL 87-001773-0A
SANDED GYP CONC PLUG MEL 97-001772-0A (TYP 6 PLCS)
LLNL STEMMING FINES MEL 75-001282-0E (TYP 6 PLCS)
MAGNETITE MEL 76-001300-0B
BORON RICH MATERIAL MEL 86-001761-00
BACKFILL
CABLE FANOUT LOCATIONS
293'
353'
566'
625'
852'
891.5'
1121.5'
1163'
1417'
1458.5'
1703.5'
(1703.0')
1772'
296'
(337')
336'
(349')
346'
569'
(568')
609'
(610')
619'
(620')
855'
(852')
875'
(874')
885'
(886')
1130'
(1151')
1150'
(1162')
1160'
1420'
(1417')
1440'
(1451')
1450'
1709'
(1708')
1759'
1769'
(1850')
1858'
1966'
(1965')
1995'
2250'
(AS BUILT)
DOWNHOLE WT.
682.7K (789.0K)
STEMMED WT.
1295.1K (1211.0K)
HOLMES & NARVER-AREA 2
12/05/99
309C00726


AS-BUILT CONFIGURATION
U20az
REVISIONS
LTR DESCRIPTION DATE APPROVED
OA REVISED ELEV 1D-DA, DB & DC & ADDED ALL ELEV., C COTTON 6-22-89 T BROWN
OB ADDED STA NO. 86SG, 89SG, 3ACT, ACR. DELETED STA NO. 93PX, REVISED CONFIG. REFD TO LATEST CONFIGURATION. STA'S 30PX, 31PX THRU 36PX, RA CHANGED TO 31PX, RA THRU 39PX, RA, STA 39PX, RA, ACC CHANGED TO 131PX, RA, ACC. H. WATKINS 8-6-89 T BROWN
OC REVISED TO AS-BUILT CONFIGURATION. H. WATKINS 1-2-90
DEPTH FEET (METERS)
1970.0'
992.9'
50.0'
67TH
3.0 (0.91) 63UV, AV
3.0 (0.91) 62UV, AV
3.0 (0.91) 61UV, AV
BOTTOM OF LINER 39.5 (12.04)
286.0 (80.22)
10.0 (3.05) 88SG
238.0 (71.93) 86LV
337.0 (102.71)
GYPSUM CONCRETE PLUG
381.0 (110.03) 131PX, RA, ACC
38PX, RA
GYPSUM CONCRETE PLUG
508.3 (154.92) 85LV
568.0 (173.12)
554.0 (168.86) 36PX, RA
610.0 (185.92)
634.0 (193.24) 37PX, RA
794.5 (242.15) 84LV
852.0 (259.68)
840.0 (256.03) 38PX, RA
874.0 (266.38)
GYPSUM CONCRETE PLUG
900.0 (274.32) 39PX, RA
GYPSUM CONCRETE PLUG
1070.0 (326.14) 83LV
1130.0 (344.42)
1115.0 (339.85) 34PX, RA
1151.0 (350.81)
1175.0 (358.14) 33PX, RA
1362.6 (415.30) 82LV
3ACT, ACR
2ACV, ACT, ACR
1ACV, ACT, ACR
1417.0 (431.88)
1440.00 (438.91)
GYPSUM CONCRETE PLUG
1405.0 (428.24) 32PX, RA
1460.8 (445.23) 31PX, RA
1653.4 (503.93) 81LV, CX/EX
GYPSUM CONCRETE PLUG
1708.0 (520.57)
1838.5 (560.83) 88SG
1759.0 (536.14)
1963.41 (598.42) 99 AM
1963.41 (598.42) 98 AM
1963.41 (598.42) 97 AM
1963.28 (598.38) 96CX
1963.20 (598.35) 95CX
1963.29 (598.38) 92CX/EX
1963.20 (598.35) 91CX/EX
1963.32 (598.39) 81CX/EX
TOP OF DIAG. CAN 1960.0 (596.90)
1968.0 (599.82) RD
STA NO. PROBE PROBE DEPTH
86E CP 286.7
86D CP, TS 301.7
86C CP, TS 311.7
86B CP, TS 321.7
86A CP, TS 331.7
85E CP 580.2
85D CP, TS 574.2
85C CP, TS 584.0
85B CP, TS 594.0
85A CP, TS 604.0
84D CP, TS 855.0
84C CP, TS 860.0
84B CP, TS 865.0
84A CP, TS 870.0
83D CP, TS 1130.0
83C CP, TS 1135.0
83B CP, TS 1140.0
83A CP, TS 1145.0
82D CP, TS 1420.0
82C CP, TS 1425.0
82B CP, TS 1430.0
82A CP, TS 1435.0
81E CP 1708.0
81D CP, TS 1714.0
81C CP, TS 1729.0
81B CP, TS 1744.0
81A CP, TS 1754.0
EG&G ENERGY MEASUREMENTS, INC.
Amador Valley Operations
P. O. BOX 808, LIVERMORE, CALIFORNIA 94550
SPECIAL MEASUREMENTS
PHYSICS PLAN,
BARNWELL/U20az
FSCM 99626
DRAWING NUMBER ECG89-103976-0C
SIZE C
SCALE NONE
WT
SH 1 OF 2
DRAWN L. DESAI 5-15-89
CHECKED R. GREGORY 6-1-89
DESIGNER
ENGINEER T. BROWN 6-7-89
PROJ ENGR
FILE NAME 103976-1
ORIGIN EG&G GCD REV 3.1
LEGEND
(MUX) MULTI-PLEX CANISTER
(EX/CX) EXCOR/CORRTEX
(PX, RA) STEMMING CANISTER
(TH) STEMMING HOPPER
(SG) STRAIN GAGE
(AM) ANTENNA
PIN
PINHOLE
ACT ACCELERATION (TANGENTIAL)
ACR ACCELERATION (RADIAL)
ACV ACCELERATION (VERTICAL)
SG STRAIN GAGE
ACC ACCELERATION
LV LIQUID LEVEL
CP CONDUCTIVITY PROBE
TH THERMISTOR
TS TEMPERATURE SEMICONDUCTOR
PX PRESSURE
RA RADIATION
EX EXCOR
CX CORRTEX
AM ANTENNA
2:1/2.ECG89-103976-0C

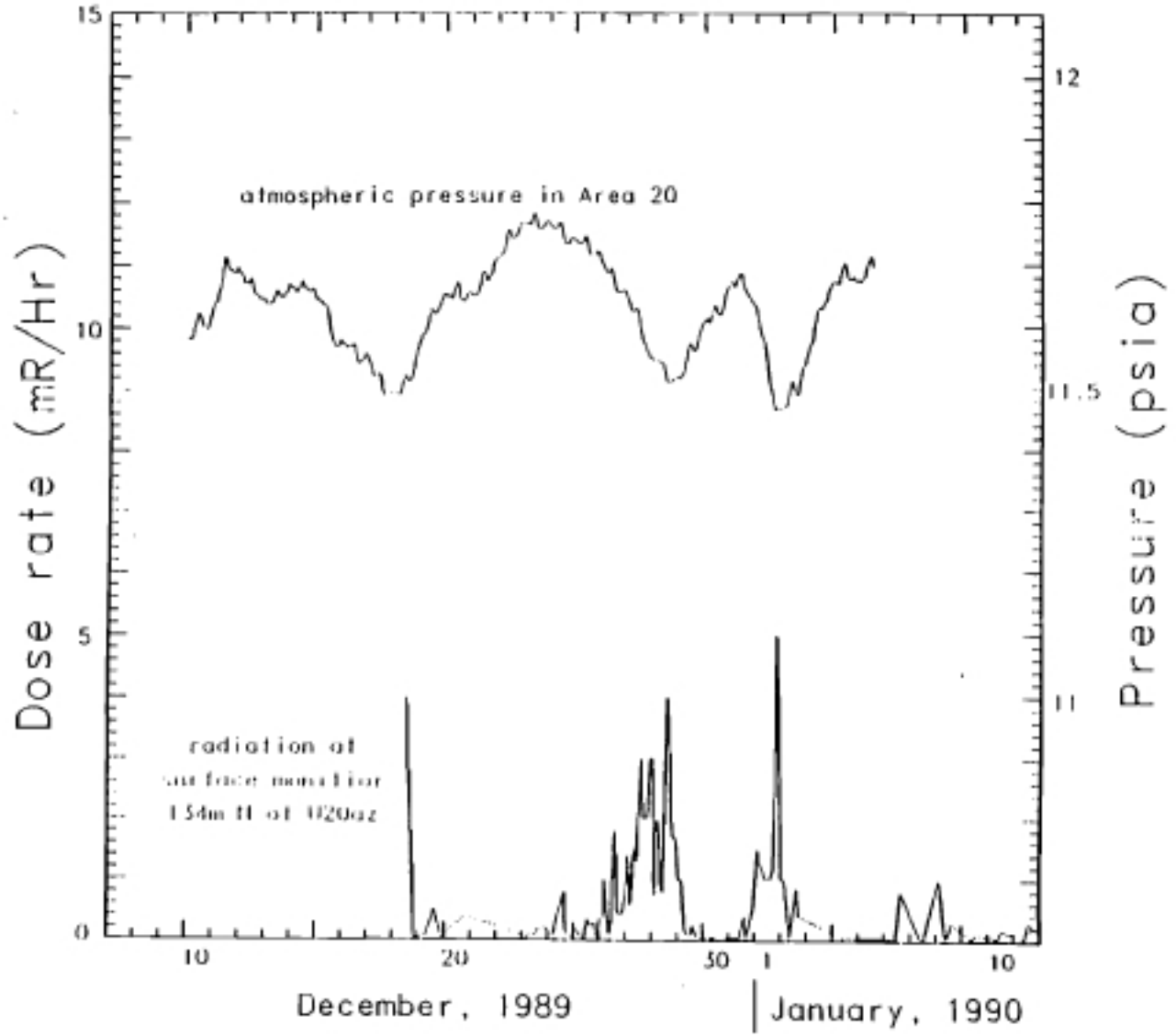

U20az
Depth M
0
200
400
600
117 m
44.2 m
18.3m
290 s
240 s
200 s
2 h
4 min
radiation
excor
strong arrival
weak arrival
10^2
10^3
10^4
10^5
Time, s

Barnwell

Elevated levels of radioactivity were observed on December 18, about 400 feet north of U20az



Each release episode occurred during a period of low atmospheric pressure



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